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Starshades for ATLAST

Final Report Input

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Startshades Enable LifeFinder Science with ATLAST

- Combining a large optical telescopes with an external occulter (starshade) enables characterization of potentially more than 100 extrasolar planetary systems.
- The high throughput of the starshade enables high resolution (R>>1000) spectroscopy of planetary atmospheres, detection of diurnal variations, polarization measurements, etc.
- The large field of view, when combined with an integral field spectrograph, allows simultaneous study of the entire extrasolar system.
- A starshade is competitive with an internal coronagraph in the number of accessible systems while facilitating deep, tailored observations of select objects.

Starshade Sizing

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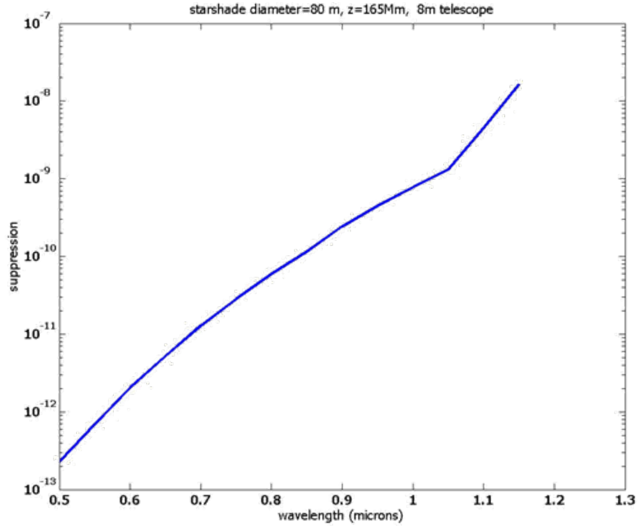
- In general, starshades work better at **shorter** wavelengths.
  - Starshade size is a fast function of wavelength if all other requirements are the same
  - However, the star/planet contrast ratio requirement goes down for longer wavelengths
  - Starshades provide higher suppression at shorter wavelengths and lower suppression at longer wavelengths
- Note that the contrast ratio in the image plane at the location of a planet is expected to 10 to 100 times better than the suppression ratio in the table below.
  - We use suppression as the ratio of the integral of remaining starlight to the amount detected over the same band pass without a starshade. This remainder will be spread over many image pixels, leading to a significantly higher contrast level.
  - This might be even better for ATLAST, where we can located the planet in the blue and then accept more stellar background in the red
- Starshade size and distance is also a strong function of IWA
  - Planets can be detected at least 20% inwards of the geometrical IWA of the starshade
  - This can be enhanced even more in the blue due to the higher suppression
- We sized starshades for the 8 m and 16 m ATLAST telescopes using the requirements listed below
- These values are highly requirements dependent; we made some judgment calls to ensure consistency

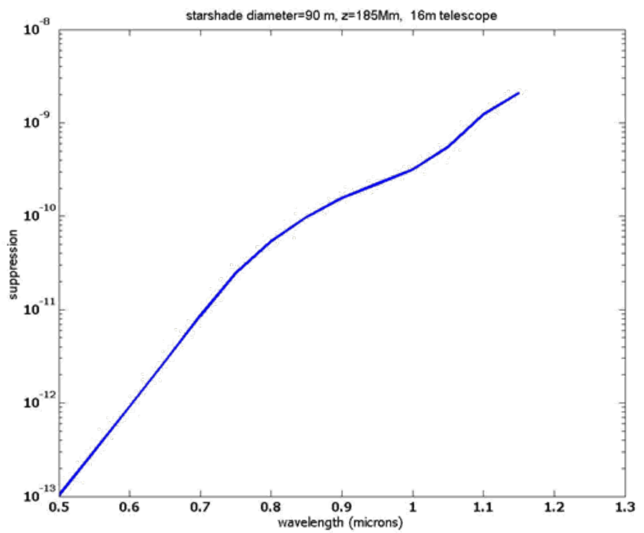
Requirements				**Derived Values**		
D_{tel}	IWA	λ_{max}	Suppression at λ_{max}	Starshade size	Starshade distance	Notes
(m)	(mas)	(microns)		(m)	(Mm)	
8	58	1	1E-9	56	80	Specified requirements → ~same as NWO!
8	39	1	1E-9	**80**	**165**	Changed IWA to 2λ/D
8	58	1	1E-7	45	63	Relaxed supp → smaller than NWO!
16	29	1	1E-9	110	320	Specified requirements
16	40	1.1	1E-9	**90**	**185**	Relaxed IWA req.
16	29	1	1E-7	90	250	Relaxed suppression req.

Starshade Sizes Chosen for ATLAST Study

- For the 8 m telescope, we chose a starshade 80 m in diameter, 165,000 km from the telescope for further study
  - This provides an effective IWA of 40 mas
  - The suppression performance vs. wavelength is shown to the right



- For the 16 m telescope, we chose a starshade 90m in diameter, 185,000 km from the telescope for further study
  - This provides an effective IWA of 40 mas
  - The suppression performance vs. wavelength is shown to the right



Note that the graph shows suppression rather than contrast (see notes).

NWO + ATLAST: Orbits

Set top level limits on orbits and permissible telescope-starshade separation

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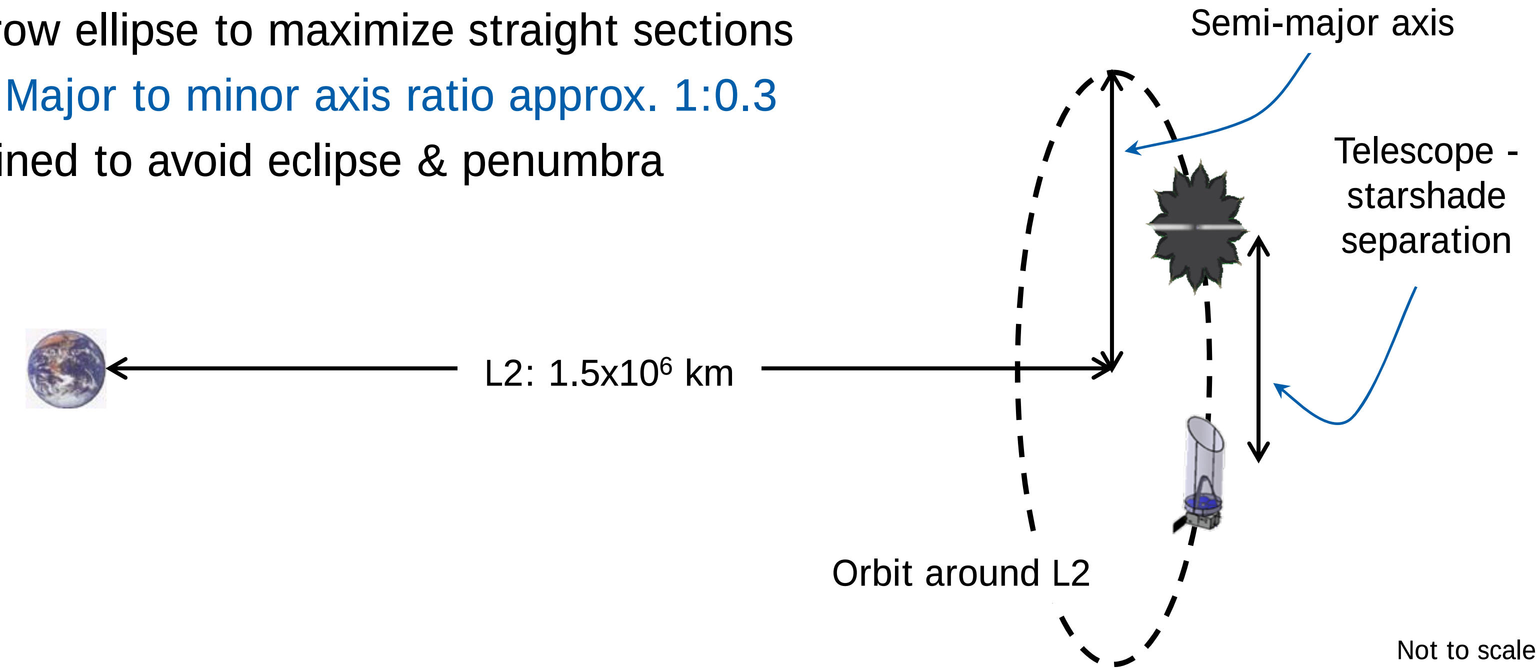
- A family of solutions exists for orbits around L2
  - L2 orbits require ~5 m/s of ΔV per year to maintain the orbit
- Ideal starshade orbits start at orbits with semi-major axis much larger than the starshade-telescope separation
- For large starshade separation, orbits should be:
  - narrow ellipse to maximize straight sections
    - Major to minor axis ratio approx. 1:0.3
  - Inclined to avoid eclipse & penumbra



ATLAST Orbital Limits

- The ATLAST starshades have separations of 165,000 km and 185,000 km
- Orbital limits
  - Semi-major axis should be ~400,000 km or larger
  - Semi-major axis should be ~900,000 km or smaller
  - **Ideal size between 600,000 km to 800,000 km**
- Larger orbits:
  - Require more fuel for stationkeeping
  - Stationkeeping error increases risk of rapid deorbit (kick out)
- Smaller orbits:
  - May incur eclipses and penumbra shadowing
  - Significantly limit FOV and look direction
  - Significantly limit usable portion of the orbit
- **Current restriction on maximum separation: ~300,000 km**
  - Usable portion of orbit remains high, at least 50%
  - Total FOV is full 4π
  - If these requirements are relaxed, then separation can be larger

Estimate of Maximum Number of Targets Observable with 16-meter Telescope

- Goal was to determine how many stars the 90 m starshade with the 16 m telescope can observe in 5 years
- Started with the 1010 stars on the list provided by M. Postman
  - These have an average exposure time of 2 days
  - On average, 1010 stars would be ~7 degrees apart if they were spread evenly on the sky
- On NWO, we use 2 NEXT SEP thrusters for the retargeting maneuvers. For ATLAST, we used various numbers of thrusters to estimate the number of possible observations.
- We did some basic scaling to estimate the expected number of stars we could observe in each case:

Number of thrusters	**Time for 7° slew**	**Av. observation cadence**	**Total observations in 5 years** (4 years available for slewing)	**Percent of time (5 years) spent observing**
4	11.19 days	~13 days	138	15
8	8.29 days	~10 days	177	19
16	6.34 days	~7 days	218	24

Using Mission Planner to Find Optimal Path for 16-meter telescope

- We ran our Starshade Design Reference Mission (DRM) tool with the configuration for the 16 m ATLAST to generate the best possible observing schedule and statistical fuel usage estimates
- Ground rules:
  - Exposure times from spreadsheet provided by M. Postman for 1010 target stars
  - Stars were prioritized by 1/exposure time
  - 5 year mission was simulated
  - 4, 6, or 8 NEXT thrusters for retargeting
  - 4 Hall-effect thrusters for stationkeeping

Best individual results for each value, not on the same run

# of retarget thrusters	4	6	8
Max number of stars	148	171	192
Min stationkeeping Δv (m/s)	181	150	174
Min retargeting Δv (m/s)	10,500	14,300	17,600

Schedules with most targets observed

# of retarget thrusters	4	6	8
Number of stars	148	171	192
Stationkeeping Δv (m/s)	487	150	381
Retargeting Δv (m/s)	10,6 00	14,300	19,300

Note: the targets observed in the best cases were generally in the southern hemisphere (below -45° Declination) because of the larger continuously viewable zones near the poles and the higher concentration of stars in the southern hemisphere

Estimate Max Number of Targets Observable with 8-meter Telescope

- For the 8 m version, we only did a simple scaling to get an idea of the number of targets that would be observable in 5 years
- There are 144 stars on the list of targets for the 8 m ATLAST, which means they are ~20 degrees apart on average (as opposed to ~7 degrees for the 1010 stars on the 16 m list)
  - We believe that there are really many more than 144 stars which would make good targets for the 8 m telescope
  - Increasing the target list will decrease the retargeting time and improve the total number of stars observed

- The results of our basic scaling calculations:

Number of thrusters	Time for 20° slew	Av. observation cadence	Total observations in 5 years	Percent of time spent observing
4	17.7 days	~20 days	93	10
8	13.1 days	~15 days	122	13
16	10 days	~12 days	153	16

Maximizing Science Return with Starshades

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- While ATLAST can search for exoplanets to larger distances than smaller telescopes, we believe that ATLAST's most valuable contribution to exoplanet science would be to fully characterize known planetary systems.
- We expect that the detection of extrasolar planets will be well advanced by the time of the ATLAST launch and full characterization would provide higher return than searches.
- With the resolution and the collecting area of a 16 m telescope, ATLAST could observe individual exo-solar systems for weeks. It could get very high resolution spectra (R>>1000) of all the planets in the system, watch for diurnal variations in their brightness and spectra, measure their polarization, watch them as they orbit, etc.
  - The IWA of an external occulter can be adjusted **on orbit** to tailor the observation to different separations between a star and planet.
  - Starshades are well suited to long observations – they provide very high throughput, so the S/N of an observation will be very high for a given exposure time, allowing observations with very high spectral resolution, very high time resolution, or both.
  - The large field of view possible with a starshade (there is no outer working angle) will allow ATLAST to look at all the planets in the system at the same time. With an integral field spectrograph, we could get high-resolution spectra of the entire field and look at the time variability of the system as a whole.
- Long observing sessions optimize the starshade's operational constraints.
  - The most fuel-intensive part of a starshade's operation is moving from one star to the next.
  - If the starshade is used to focus on the top few (tens to ~100) targets there would be less need for advanced thrusters with very high throughput and large amounts of fuel.
- A starshade that is optimized for the maximum exoplanet science return with ATLAST would look quite different from the system presented on the previous charts and would compare very favorably with other options.

ATLAST Fuel Usage Analysis

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- The main issues for the ATLAST starshade propulsion system are
  - Total propellant throughput
    - Both as a mass of fuel needed and as a thruster wear-out issue
  - Adequate thrust generation to push starshade + fuel
    - Generally, getting more thrust out of a system means more input power
- Existing technology: NEXT can be adequate
  - NEXT thrusters are (almost) available technology
    - We anticipate the next generation thruster could be more mass efficient
    - **With some development, the thrust output for next generation ion thrusters can be adjusted to ATLAST performance needs**
      - Mission cadence can be increased with higher thrust capabilities
    - Fuel throughput is probably a technology hurdle
- **Main technology hurdle is generating enough thrust**

NEXT System Limit Assessment

- The NEXT system currently has a ~500 kg Xenon throughput baseline, with an estimated 730 kg wear-out limit per thruster

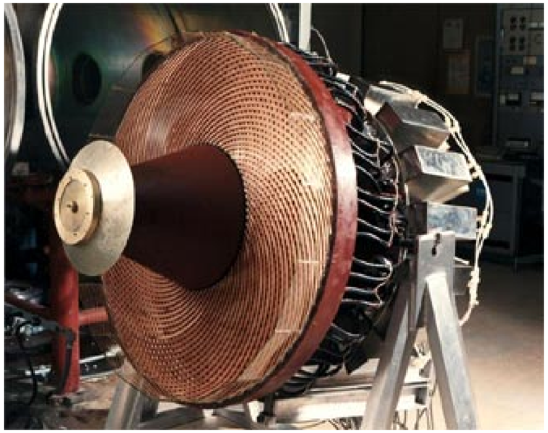
	4 Thrusters	6 Thrusters	8 Thrusters
Nom. Thruput	2000 kg	3000 kg	4000 kg
Max. Thruput	2920 kg	4380 kg	5840 kg
Max. ΔV	10675 m/s	14570 m/s	17855 m/s
# targets (optimized)	100	127	140
Fuel mass fraction	< 30%	33%	38%

- Systems beyond 8 thrusters are limited by their fuel mass fraction, so to increase performance, the Isp needs to improve
- If we can improve the overall throughput and the efficiency of the NEXT system, we can drastically improve these numbers
- These are based on a starlist of ~1010 stars, we can potentially improve the per target slew delta V with more stars on the list
  - 150 stars have an isotropic distribution separation of ~19 degrees
  - 1010 stars have an isotropic distribution separation of ~7 degrees, 2.5 x closer

PIT (Pulse Inductive Thrusters)

- High Isp system: 4000 to 8000 sec
- Low wear out: enables high throughput
- Estimated ATLAST starshade fuel mass need
  - (100 maneuvers)

System	Isp	Fuel Mass (kg)
SEP (Xenon)	4100 s	2380
PIT (Hydrazine)	8000 s	1151
VASMIR	25,000 s	354



TRW developed 1 m PIT Thruster

- Higher Isp may be reached by varying thruster design
- Potential issues include **high power requirements (kW to MW range),** lifetime qualification, and propellant vapor management
- Other technologies include VASMIR type thrusters for ultra high Isp (up to 30,000), but the power system may be too massive for serious consideration

NWO + ATLAST: TAC System Work

Trajectory and Alignment Control System

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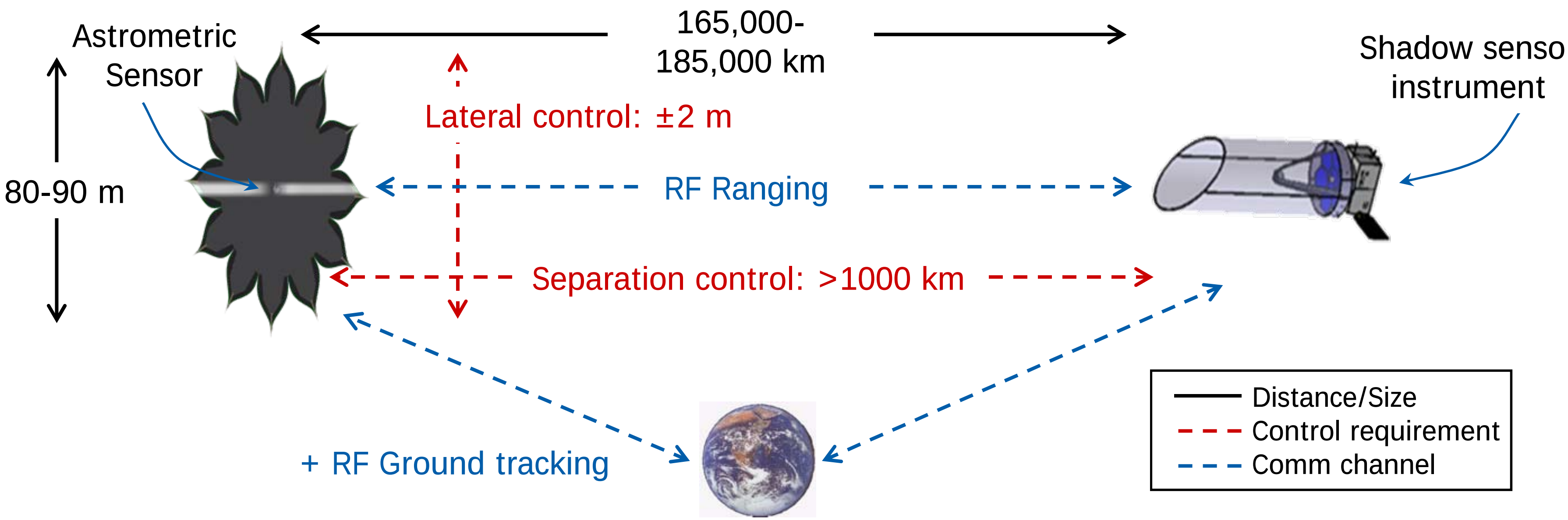

- 3 step system for trajectory and alignment control
  - Coarse: DSN/RF ground tracking
  - Medium: Astrometric Sensor on Starshade
  - Fine: Shadow Sensor in telescope focal plane
  - Augmentation by inter-spacecraft RF ranging for high accuracy separation and bearing information

TAC System Limits for Original NWO Design

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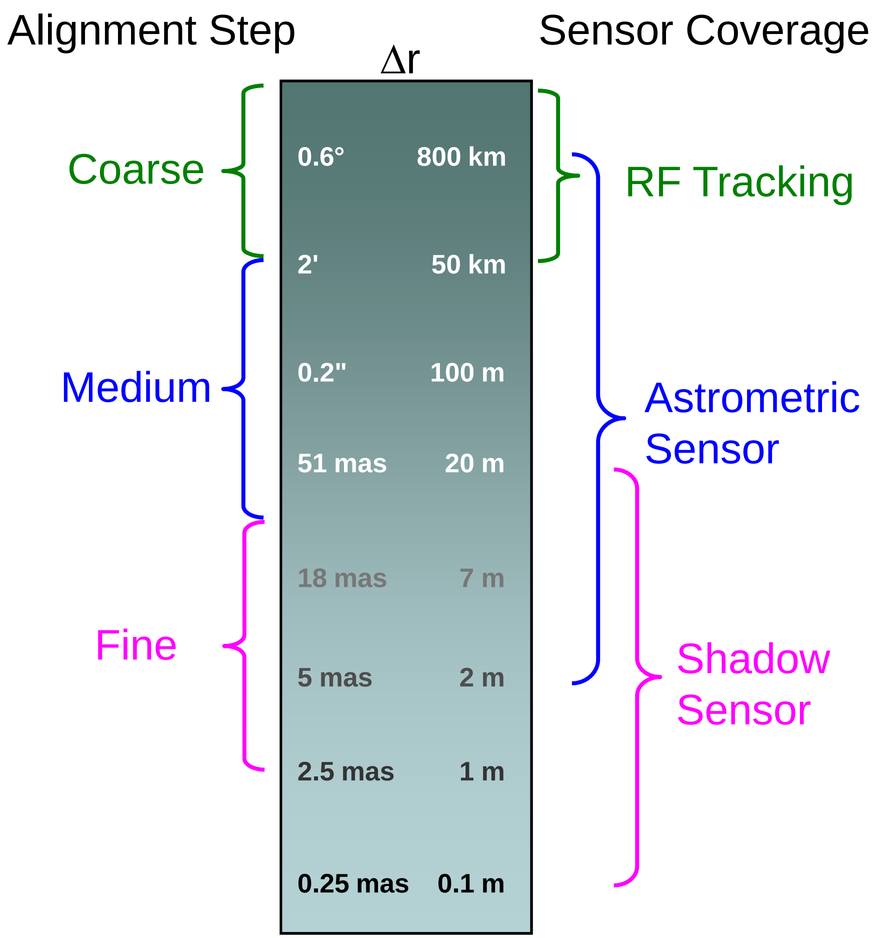
- Snapshot of the capabilities of the alignment sensors and the handoffs for the NWO TAC system
- A robust system with large spatial and angular overlaps between the control and sensing capabilities at each step
- A backup system consisting of beacons provides failure support
- During the **first few alignment maneuvers**, we expect many hours to days for the medium alignment step
- **With experience**, this alignment step should be down to a few hours, with very little telescope time until the end of the phase
  - We estimate that the time the telescope will have to be involved before beginning an observation should not be significantly more than the standard overhead for a normal observation



TAC System Limits for ATLAST

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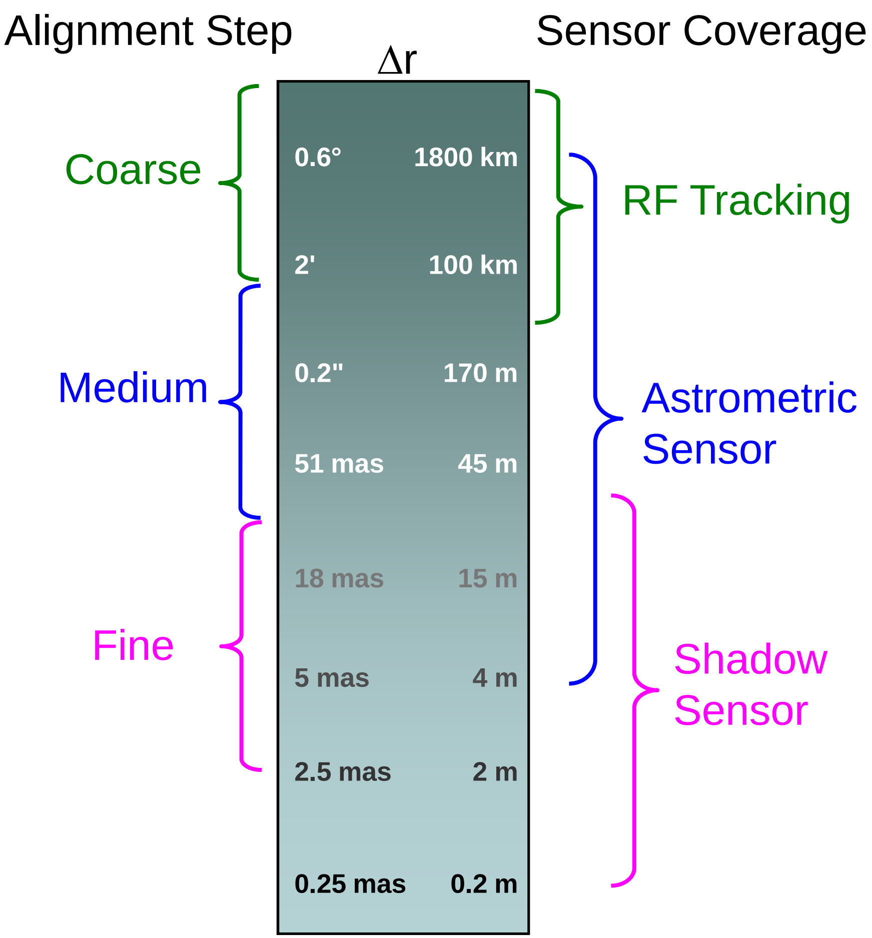
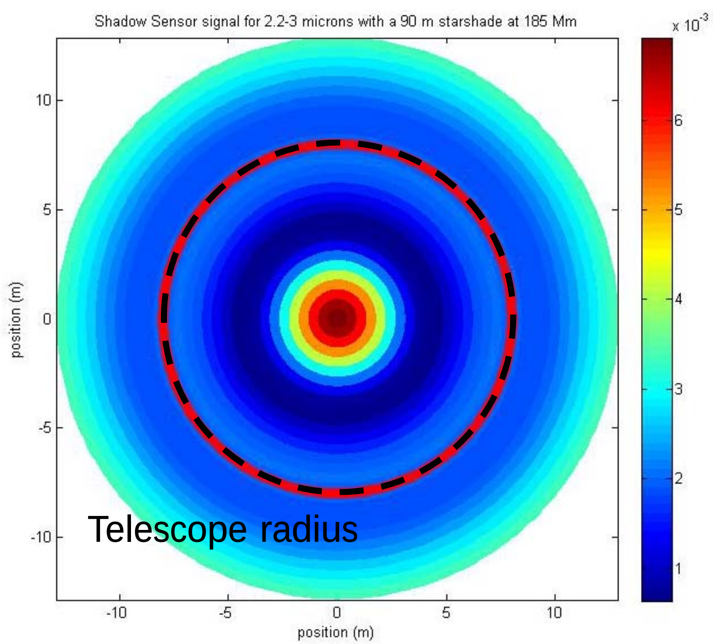
- Rough snapshot of the capabilities of the alignment sensors and the handoffs for the ATLAST + Starshade TAC system
- The same angle corresponds to a larger physical scale due to 165,000-185,000 km separation
- Fine alignment requirement is relaxed to ±2m
- Shadow onset occurs at a much larger radius. Maintains overlap between AS and SS

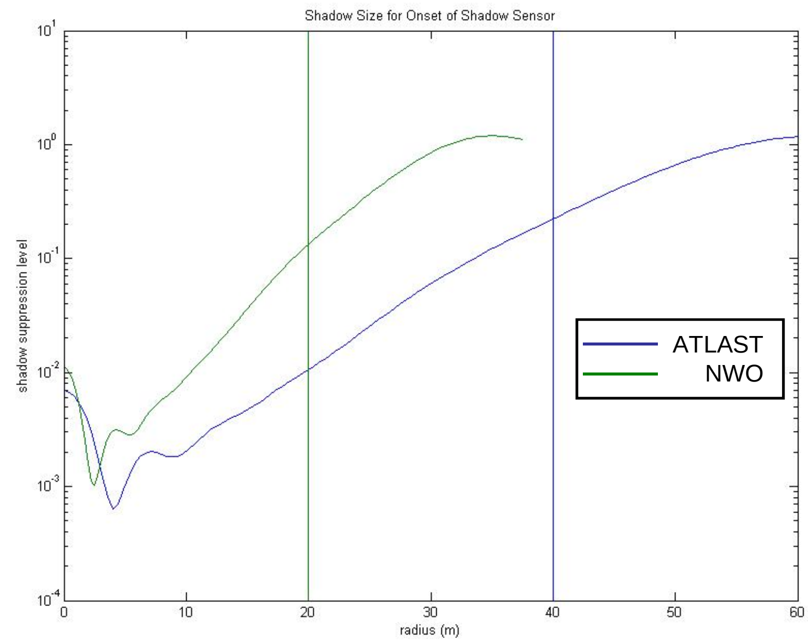


ATLAST Shadow Sensor Limits

- Simulation of long-wavelength shadow sensor image indicates many photons available
- Integration time ~1 sec for 20cm starshade position uncertainty
- ATLAST system shadow onset radius is ~2X the NWO value, well within the accuracy limit of the Astrometric Sensor
- Plot below shows the offset from the line of sight at which the shadow sensor could pick up the signal and therefore start providing alignment information



Stellar leakage for λ=1.5-3μm



NWO + ATLAST: Mass & LV Work

Existing LV Capabilities

Launch Vehicles	Interplanetary Transfer Orbit, Escape Orbit perigee altitude: 185 km, C3 = -0.6 km^2/s^2 (kg)	Interplanetary Transfer Orbit, Escape Orbit perigee altitude: 185 km, C3 = -0.7 km^2/s^2 (kg)
Atlas V 501	2715	2720
Atlas V 511	3810	3815
Atlas V 521	4595	4605
Atlas V 531	5270	5275
Atlas V 541	5885	5895
Atlas V 551	6400	6410
Delta IV M+ (5,2)	3257	3270
Delta IV M+ (5,4)	4640	4650
Delta IV Heavy	9395	9410

Largest existing fairing diameter is 5 meters

Starshade faces both a **volume** and **mass** issue

Existing Delta IV Heavy Capability: Mass

- Lift Capability to C3 = 0 too low
  - Not enough energy for direct to L2
  - Need ~14,000 Kg to L2 Capability
- May use integral 3rd stage propulsion assuming SEP ISP = 4000s and NEXT thrust level
  - May require boosting via many orbits through the radiation belt
- High power PIT performance may be an alternative
  - Requires large power source development
  - Requires qualification of PIT engine

Existing Delta IV Heavy Capability: Volume

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- **5 Meter Fairing Too Small**
  - Volumetric deployment & packaging can be done, but ratio of sizes shows issues (see box on right)
  - Deployment study required to verify actual fairing diameter required

Fairing Requirement vs. Existing Delta IV H

Starshade Diameter:	1.80x
Blanket volume:	3.24x
Stowed Length increase:	1.80x
Fairing diameter for blanket:	1.34x
Boom diameter increase:	0.2 m
Min fairing req.:	7.11 m

Single Launch Option for 8 m ATLAST Existing Technology

- For a given set of requirements, the starshade for the 8m ATLAST telescope is the same as the NWO flagship, so it can be accommodated within existing LVs
  - For increase fuel capability, the Delta IV H may be needed to lift extra fuel mass
  - Flagship NWO starshade has 17% launch margin to the Atlas V 551, and can therefore carry an extra set of thrusters and fuel for another 30% increase in targets
- For an 80m starshade, the compaction ratio is similar to that faced by the 90m, see next slides for comments.

Single Launch Option for 16 m ATLAST Delta IV H Development

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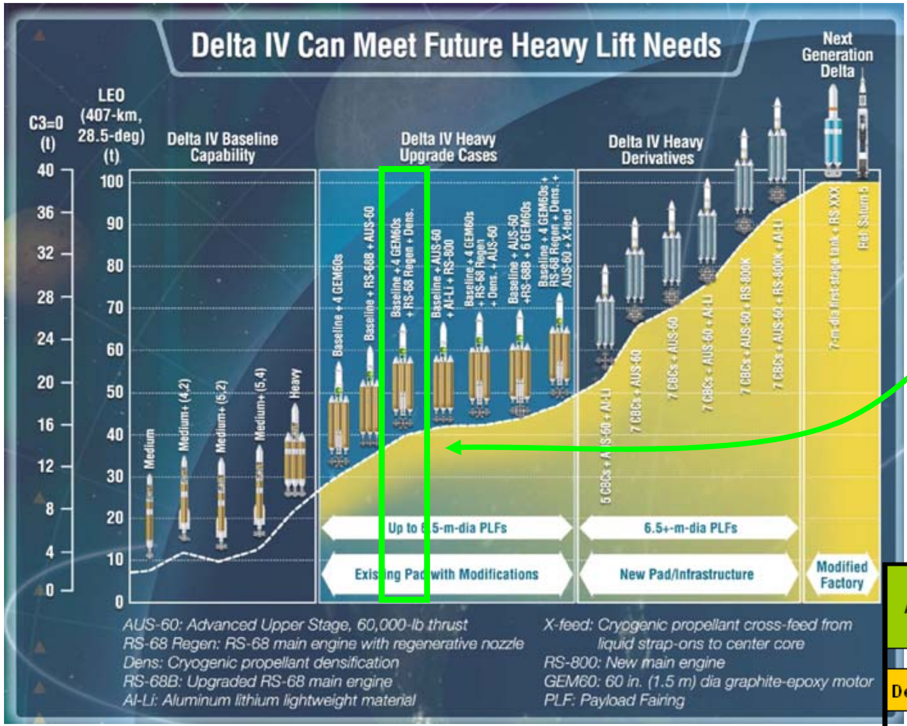

Large diameter Delta IV H, and upgraded mass

Enables single launch for the starshade

Atlast SS/V (wet) projected mass =	12849	Kg's	Includes ==>	3266	Average maturity based contingency
Delta IV Heavy Upgrade with 7 Meter Fairing*	14000	Kg's			
Current mass margin =	1151	Kg's		9%	

Delta V Assumptions:
SS/V Slewing Delta V = 8175 m/sec
SS/V Station Keeping (Translational) Delta V = 1920 m/sec
Orbital Insertion Delta V = 150 m/sec

Assembly Level						Unit mass (Kg's)	Qty	Today's nominal mass estimate (Kg's)	Maturity based contingency (%)	Projected growth (Kg's)	Total projected (with contingency) mass (Kg's)
Level 1	Level 2	Level 3	Level 4	Level 5	Level 6						
Starshade Spacevehicle (wet)								9583	34%	3266	12849
	Occultor spacecraft Propellant Load							2594	35%	908	3501
	112 Meter* Starshade Payload Assy							4509	33%	1491	6000
	Starshade Alignment Payload Assy							100	35%	35	135
	Starshade Spacecraft Assy							2380	35%	833	3212

Delta IV H with 7m Fairing

- If we assume a delta IV H with a 7 m fairing, we can resolve the volume issue
- If we assume two launches for the starshade, & dock the two components in orbit, we can resolve the mass issue
  - One launch with Delta IV H, and one with Atlas 551
  - Two docking scenarios:
    - L2 docking and assembly
    - Cis-lunar docking and assembly

Fully assembled, dual launch configuration

Assembly Level		Unit mass (Kg's)	Qty	Today's nominal mass estimate (Kg's)	Maturity based contingency (%)	Projected growth (Kg's)	Total projected (with contingency) mass (Kg's)
Level 1	Level 2						
Starshade Spacevehicle Assembly (wet)				**11166**	**34%**	**3820**	**14986**
	SS/V 1			**6323**	**34%**	**2125**	**8449**
	SS/V 2			**4843**	**35%**	**1695**	**6538**

Dual Launch Preliminary Mass Analysis: L2

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L2 docking and assembly

Delta IV Heavy with 7 Meter Fairing

Atlast SS/V 1 (wet) projected mass =	8449	Kg's	Includes ==>	2125	Average maturity based contingency
Delta IV Heavy With 7 m Fairing to L2	8675	Kg's			
Current mass margin =	226	Kg's		3%	

Delta V Assumptions:
SS/V 1 Slewing Delta V = 0 m/sec
SS/V 1 Station Keeping (Translational) Delta V 0 m/sec
SS/V 1 Orbital Insertion Delta V = 60 m/sec

Assembly Level						Unit mass (Kg's)	Qty	Today's nominal mass estimate (Kg's)	Maturity based contingency (%)	Projected growth (Kg's)	Total projected (with contingency) mass (Kg's)
Level 1	Level 2	Level 3	Level 4	Level 5	Level 6						
Starshade Spacevehicle 1 (wet)								6323	34%	2125	8449
	SS/V 1 Propellant Load							273	35%	96	369
	112 Meter* Starshade Payload Assy							4509	33%	1491	6000
	Starshade Alignment Payload Assy							100	35%	35	135
	Docking Mechanism - Passive Half							45	35%	16	61
	Starshade Spacecraft 1 Assy							1395	35%	488	1883

Atlas V 551

Atlast SS/V 2 (wet) projected mass =	6538	Kg's	Includes ==>	1695	Average maturity based contingency
Atlas V - 551	6600	Kg's			
Current mass margin =	62	Kg's		1%	

Delta V Assumptions:
SS/V Assembly Slewing Delta V = 8175 m/sec
SS/V Assembly Station Keeping (Translational 1920 m/sec
SS/V 2 Orbital Insertion Delta V = 150 m/sec

Assembly Level						Unit mass (Kg's)	Qty	Today's nominal mass estimate (Kg's)	Maturity based contingency (%)	Projected growth (Kg's)	Total projected (with contingency) mass (Kg's)
Level 1	Level 2	Level 3	Level 4	Level 5	Level 6						
Starshade Spacevehicle 2 (wet)								4843	35%	1695	6538
	SS/V 2 Propellant Load							2770	35%	969	3739
	Docking Mechanism Assy - Active Half							91	35%	32	123
	Starshade Spacecraft 2 Assy							1982	35%	694	2676

Bottom Line for Delta IVH LV

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- Need volume upgrade in order to accommodate both 80 and 90 m starshades. Current estimate is we need a 7m class fairing
- Dual launch is needed with existing Delta IVH capabilities:
  - starshade assembly on a Delta IVH
  - Propellant module with an Atlas 551
  - Some extra 2000 kg for docking
- If launch mass was improved for the Delta IVH, from ~9000 kg to 14,000 kg, a single launch can be possible for the 90m starshade, again, with the fairing diameter to 7m
- Current Delta IVH capability restricts us to a ~75m class starshade for a single launch with no added capabilities
  - We may still have a stowed blanket volume issue

Conclusion

- Starshades scale well to be used with the aperture sizes considered for ATLAST.
- Required technology is well understood extension of existing materials and techniques (no miracles required).
- The starshade for the 8-meter version can be accommodated on existing launch vehicles. The 16-meter version fits well within an Ares V launch vehicle and might be launched on upgraded versions of existing launchers.
- Lower density material and lower mass deployable mechanisms might enable larger starshades on existing LV.
- Starshades open exoplanet science for ATLAST and are particularly well suited for deep characterization of systems while competitive with other methods in the search mode.

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Old Results from 2008

NWO Starshade Baseline

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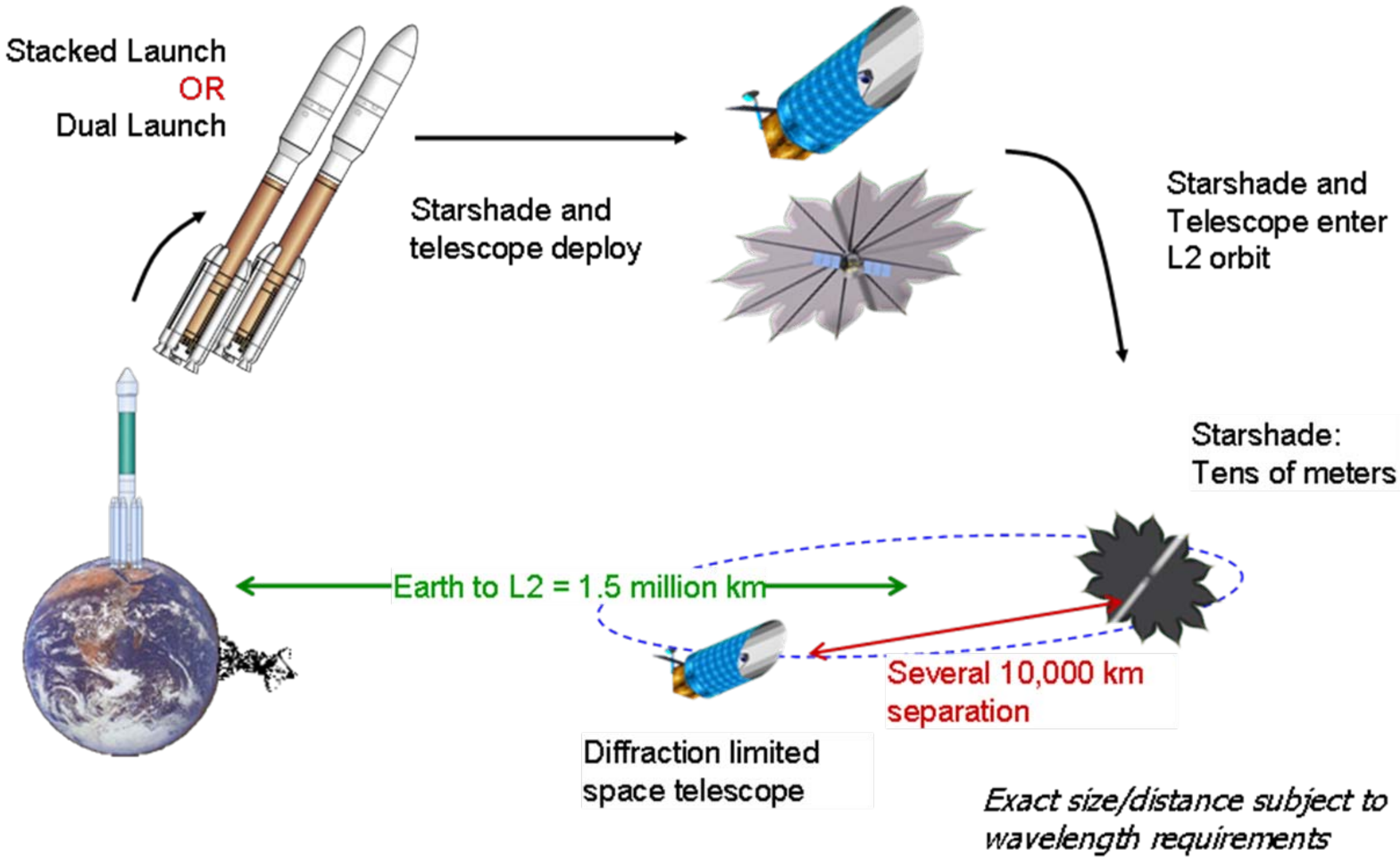

Starshade Has Little Impact On Telescope

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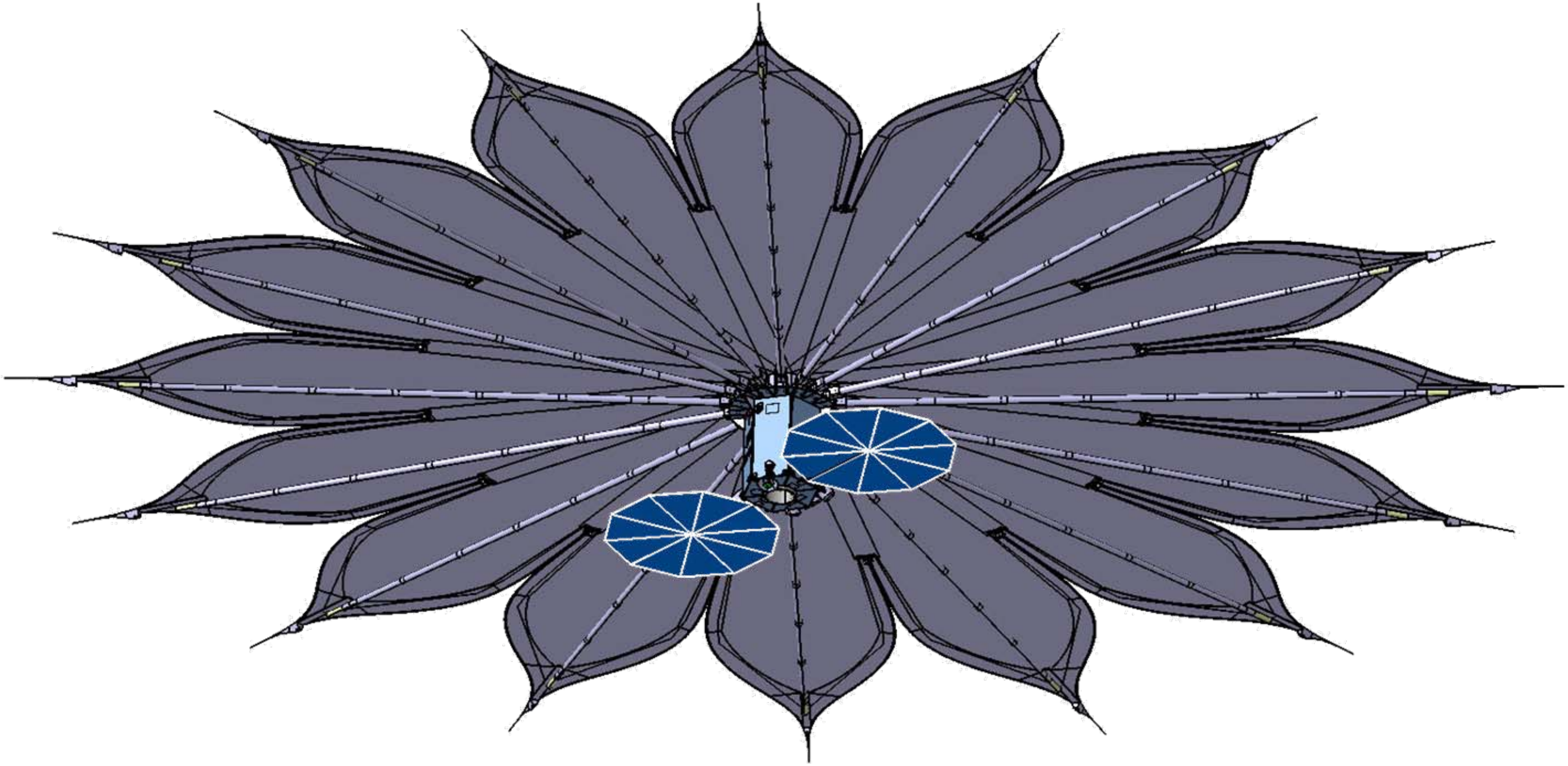
- Need cooperative Trajectory and Alignment Control (TAC) system
  - Beacons and sensors are needed on the telescope
  - Use the focal plane to help with alignment
    - During an observation, telescope needs to communicate with starshade
- Observation/Operations cadence with telescope need to be carefully coordinated to maximize science return of both Exo-planet study and General Astrophysics
- Depending on desired viewing geometry, telescope may need large baffle to enable observation at small sun angles (~50 degrees)
- Little to no impact on telescope optical design
  - Ultimate IWA depends on telescope PSF (starshade residual convolved with PSF to get planet contrast capability at the detector)
  - No thermal or mechanical design impacts other than required for TAC system

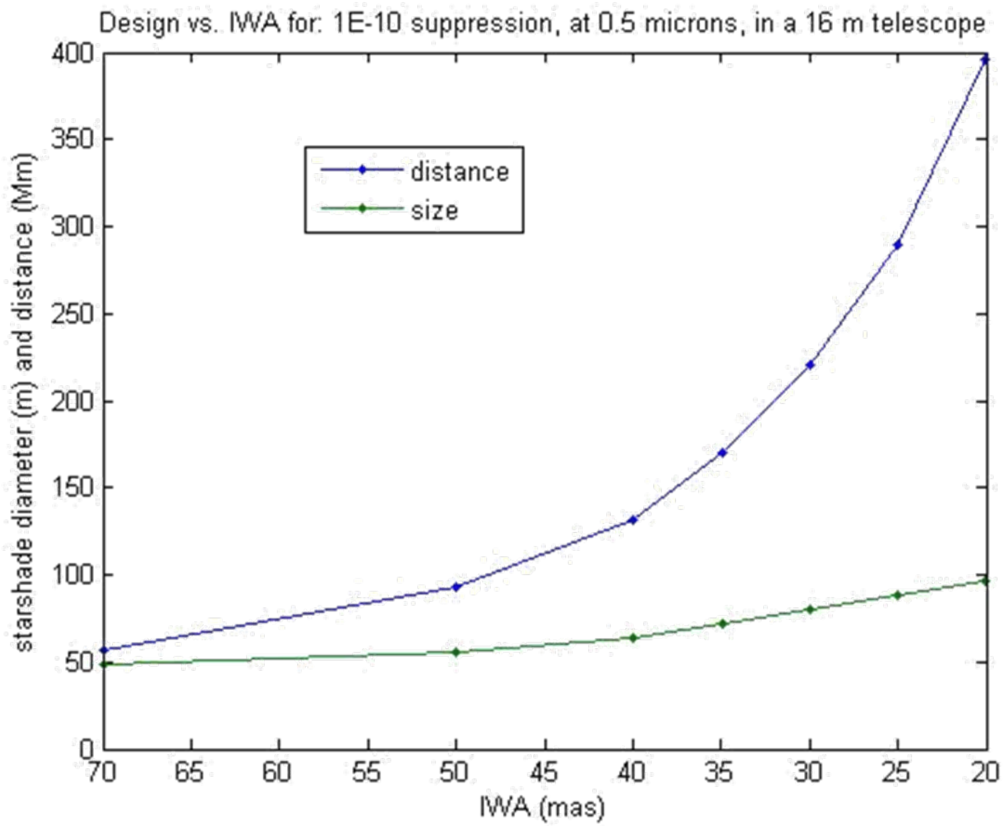
Starshade Baseline: “Blooming Onion”

NWO Starshade Design: Dean Dailey (NGST)



Flexible Design Accommodates Science Goals

- We can design the starshade for a variety of IWA, contrast, and telescope apertures
- Here is a snapshot of the starshade diameter vs. the desired IWA



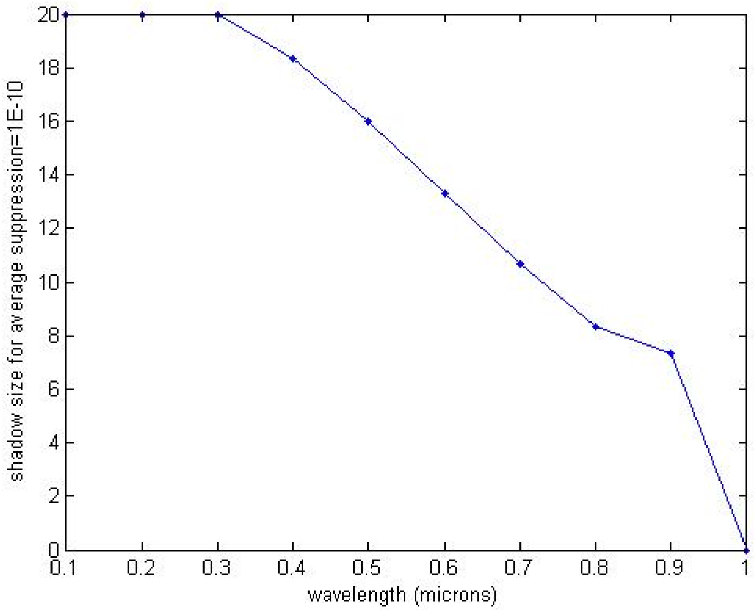
Starshades can be designed for a variety of science requirements

Starshades For Large Telescopes

- Starshades designed for 0.1 to 1.0 micron wavelength
- Baseline values only; IWA and Suppression can be changed *in orbit*

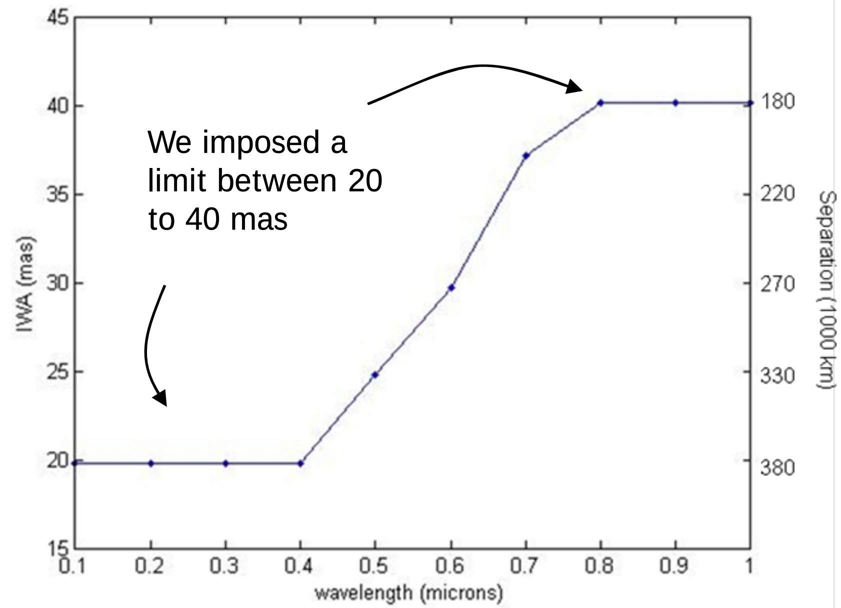
Parameter	**Starshade for 16 m**
Starshade size (~diameter)	90 m
Nominal Separation	185,000 km
Suppression, 0.5 micron	5×10^{-13}
Suppression, 1.0 micron	3×10^{-10}
IWA	20 mas → 40 mas
Planet Light Throughput	100% (~80% @ F.P.)
Wavelength range	0.1 – 1.0 micron

Starshades are Flexible In Orbit



Starshades produce very high suppression in the blue and UV wavelengths

Shadow size is a function of wavelength, which can lead to smaller IWA for short wavelengths, by moving starshades farther away



IWA & Contrast can be Adjusted In Orbit to Respond to target star characteristics

Mission Planner to Generate Best Path

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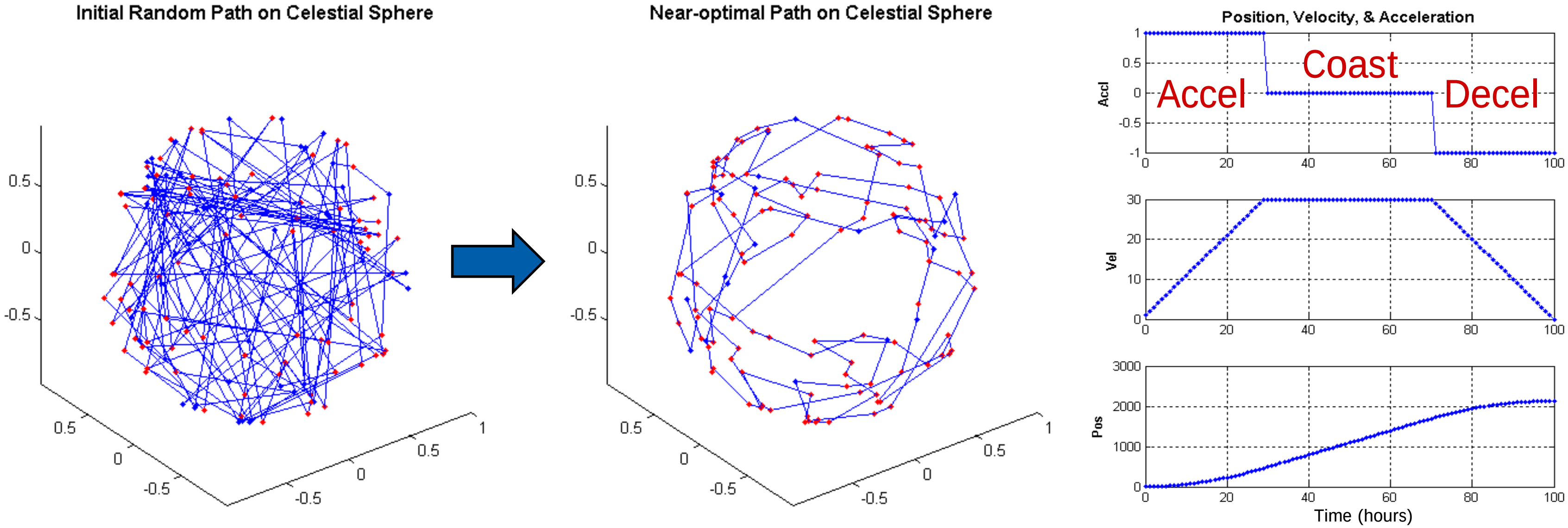
- Completeness = probability of finding a planet in the HZ around the star if $\varepsilon_{Earth}=1$
- We are in the process of developing a mission planner to optimize the DRM



- For ATLAST, we assume search is finished, and starshade used for characterization
  - Possible science includes atmospheric compsition analysis with R ~3000 spectra, surface terrain deconvolution mapping with high S/N photon variation counts, cloud coverage statistics

Starshade Observation Scenario

- The mission planner is flexible and can take many inputs, for this presentation, we made the following assumptions
  - 2 week observation of target
  - 50 target stars in the sky, with known planets, and at least first order knowledge of planet orbit
  - 4 NEXT thrusters for point to point retargeting
  - 4 Hall effect thrusters for stationkeeping

# targets / year	Retargeting Delta V	Stationkeeping Delta V
9	~1838 m/s	~ 88 m/s
12	~1670 m/s	~510 m/s

30% margin included

- For characterization heavy scenarios such as ATLAST, fuel efficient stationkeeping propulsion system is needed
- We baseline the Hall Effect thrusters, but much more efficient systems may be available by 2020's

Preliminary Mass Rack Up

- CBE mass rack up, with 30% contingency, baseline 9 targets/year

Starshade (90m)	MASS	
Component Description	Total Mass w/out Cont (kg)	Total Mass w/ Cont (kg)
PAYLOAD	5579.8	7103.7
SPACECRAFT BUS	2302.9	2993.8
SPACE VEHICLE DRY MASS (KG)	7882.6	10097.4
PROPELLANT MASS - Retarget (KG)	2263	2263.0
PROPELLANT MASS - Stationkeep (KG)	979	979.0
TOTAL WET MASS (KG)	11125	13339.4

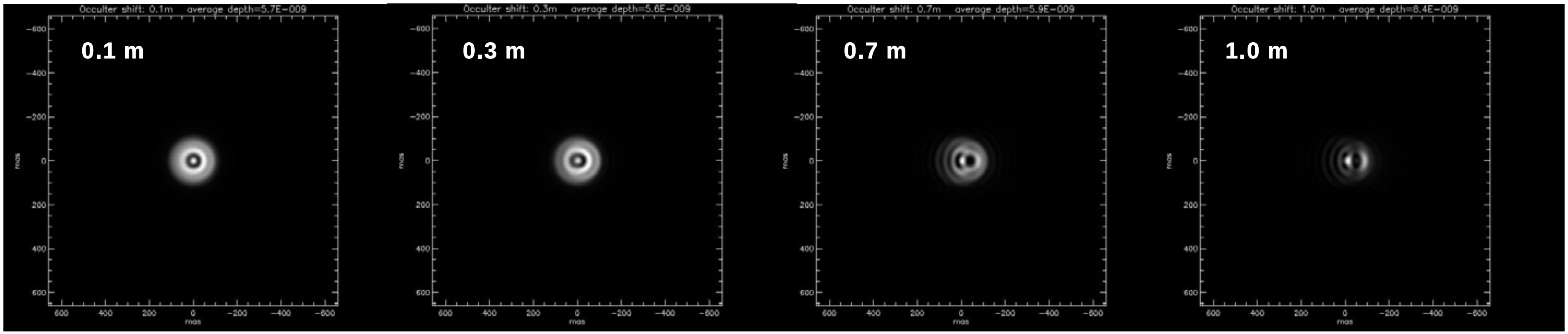
- The ATLAST shade is easily accommodated inside an Ares V launch vehicle
  - Compaction ratio is less than the NWO flagship class mission
  - There is excess mass margin
- We need to do more work to refine the equipment list and budgets, this is a first order estimate using scaling relationships from the 50m class starshade

Suppression vs. Contrast

- We have designed for 10^{-10} suppression in the aperture plane
- Due to convolution with the telescope PSF, the contrast at the location of a potential exoplanet (well outside the IWA) will be at least 30x lower
- Suppression value of 1×10^{-10} translates to contrast of 3×10^{-11} in the pupil plane

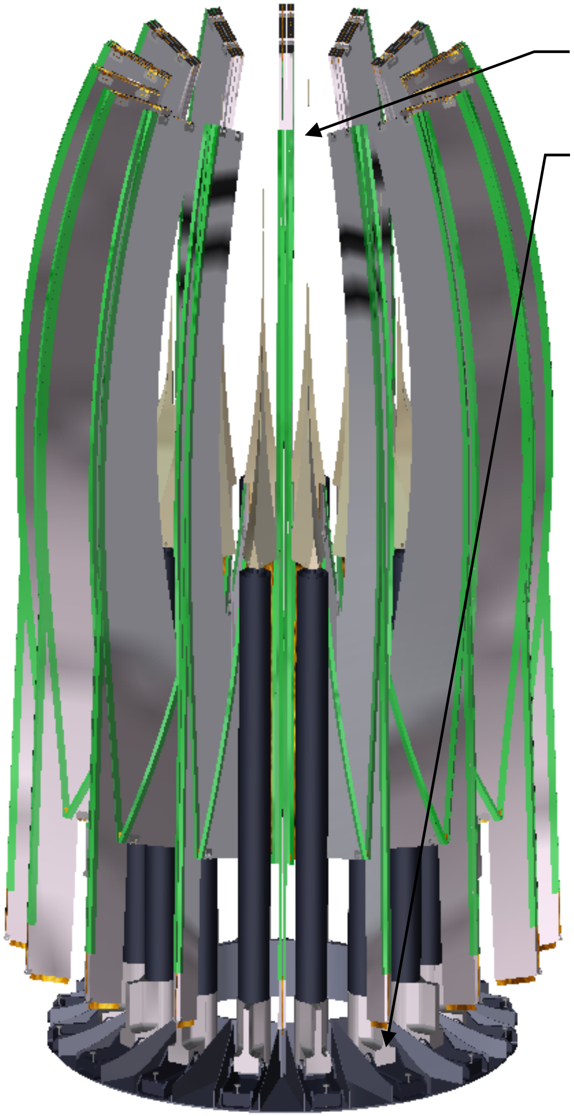
PSF Distortion Due to Errors

- As starshade moves off axis, the PSF becomes distorted



- This will occur with other classes of errors, e.g. starshade shape distortion
- Designs that are sensitive to asymmetry will need much tighter alignment requirements and tighter tolerances
- The NWO baseline design easily tolerates these errors

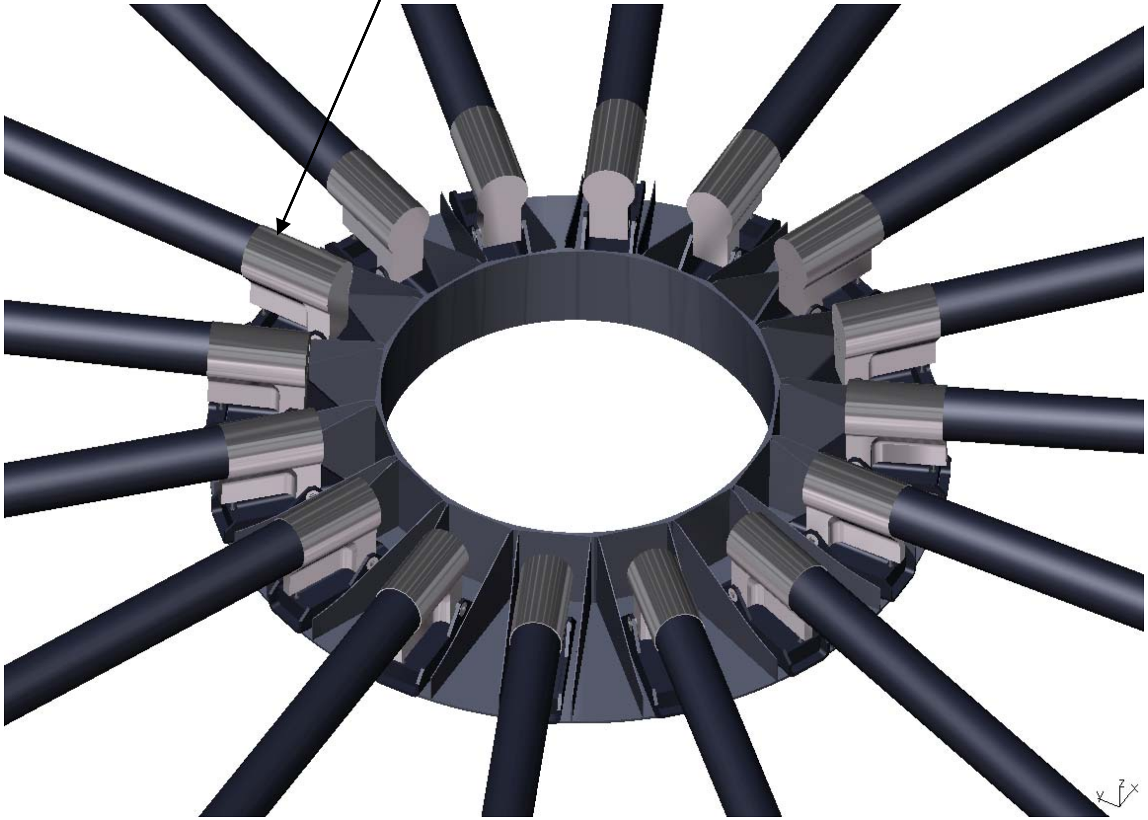
Starshade Baseline: Deployment Structure



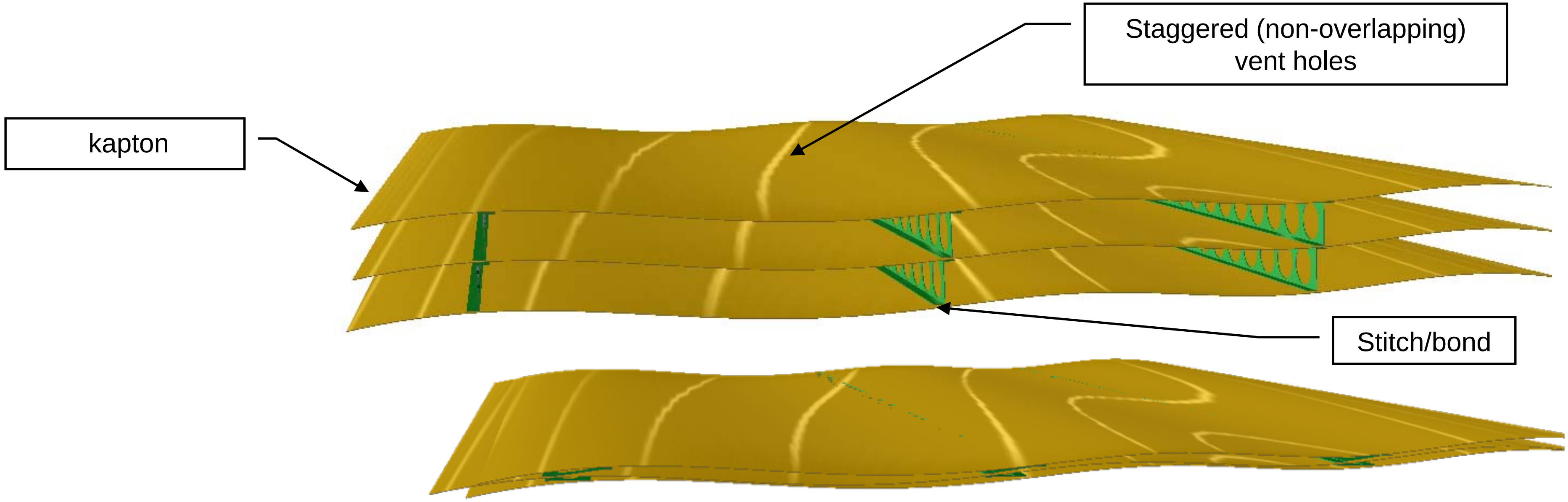
•Stowed Launch Restraints

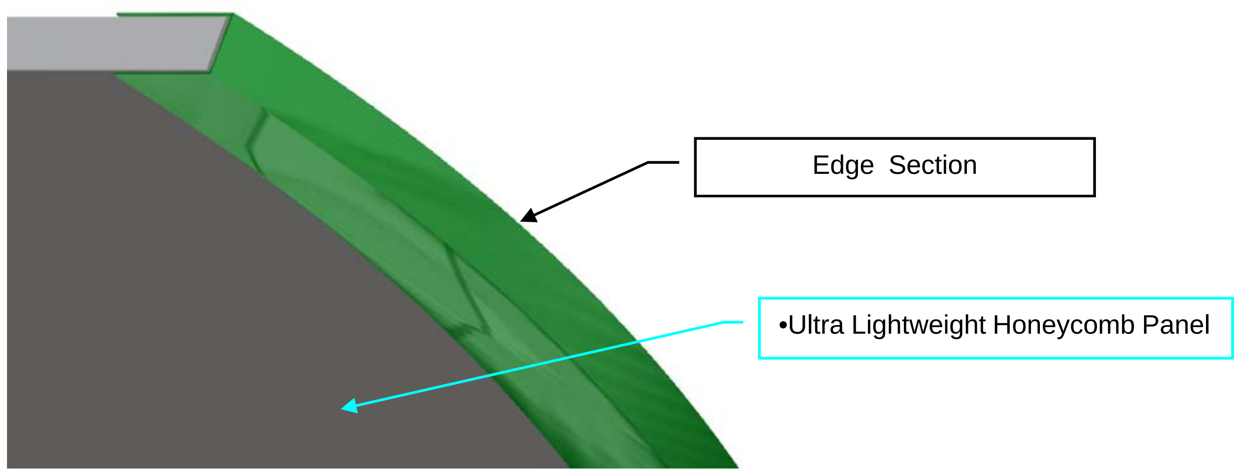
•Stowed Launch Restraint

•90 Degree Latching Root Hinges
•Housing Contains Stem Deployer/Drive Assembly for Telescoping Booms



Starshade Baseline: Fabric and Edges





Mass Mitigation Challenges for 50 m Shade

- Possible mass savings enabled by engineering development

Current Baseline	Lightweighting Option	Additional Analysis Needed	Mass Saved
3 layer (50-25-50) kapton blanket	2 layer (50-50) kapton blanker	Micrometeorite survival Thermal Analysis	74 kg
16 boom deployment	8 boom deployment	Deployment analysis	215 kg
1 mm GFRP wall thickness	0.5 mm GFRP wall thickness	Producibility and Structural Analysis	29 kg
Ultralightweight M55J graphite	Future nanocomposite at 30% density reduction	Structural and thermal loading analyses	83 kg

- Current blooming onion nominal mass + 30% margin: ~2000 kg
- Starshade design challenge, mass + 30% margin: ~1600 kg

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DEFINING THE FUTURE

A Starshade for the ACCESS Mission

April 13, 2009

Chuck Lillie

Tiffany Glassman

Amy Lo

Requirements for Starshade with ACCESS

- ~10^{-10} average suppression in a 1.5 m telescope
- λ_{max}=1 micron
- IWA=$2\lambda/D$ ~0.15”
  - There is no additional scientific gain to making the IWA less than $2\lambda/D$

Starshade Sizing

- In general, starshades work better at shorter wavelengths
- Given otherwise identical requirements, starshade size is a fast function of wavelength
  - In reality, the contrast ratio requirement goes down for longer wavelengths
  - As an exercise, we sized starshades for various wavelengths
    - All have better than 10^{-9} suppression and IWA ~0.15 arcsec with 16 petals

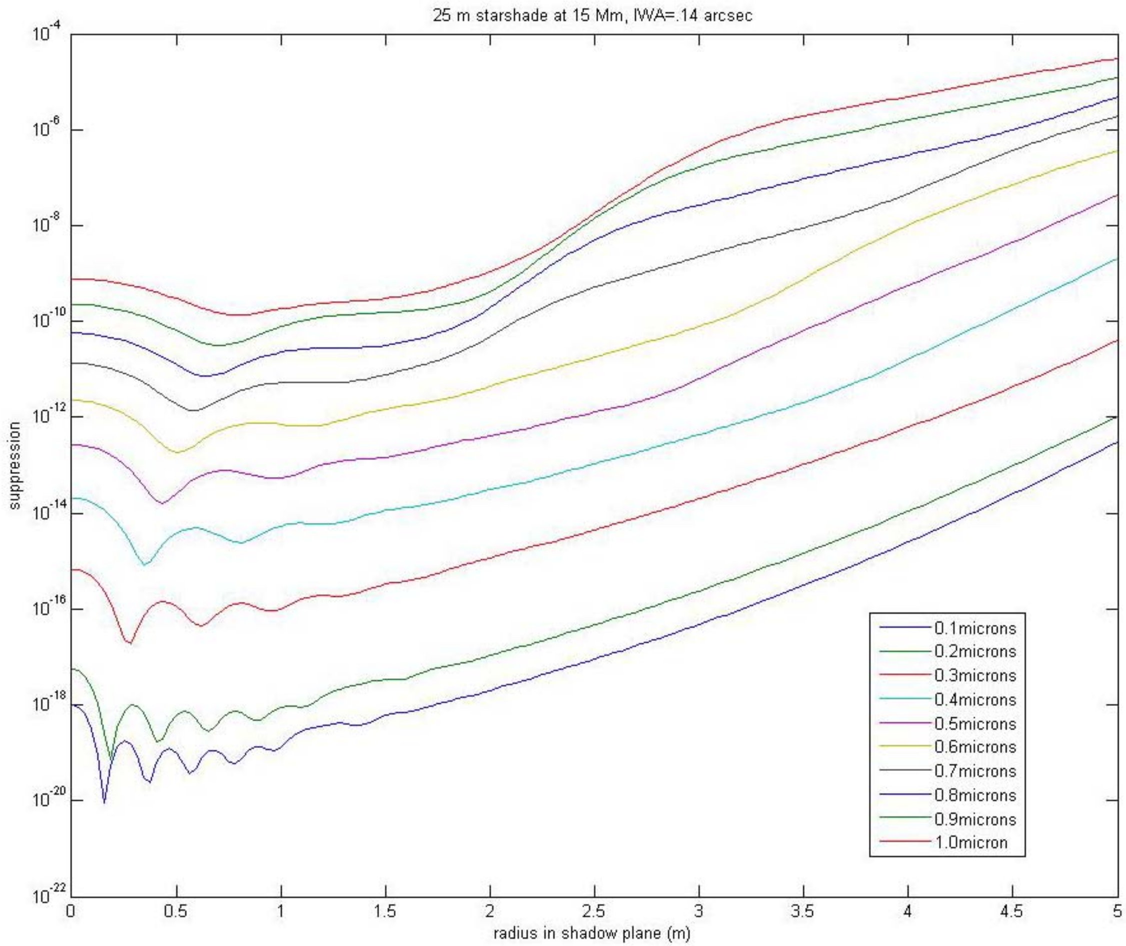
Longest Wavelength (micron)	0.5	1.0	1.5	2.0
Starshade Diameter (m)	11	22	33	44
Distance (Mm)	6	12	18	25

  - These are approximate values that are highly requirements dependent; we made some judgment calls to ensure consistency

ACCESS Starshade for λ_{max}~1.0 micron

Starshade suppression performance vs. wavelengths for the ACCESS baseline:

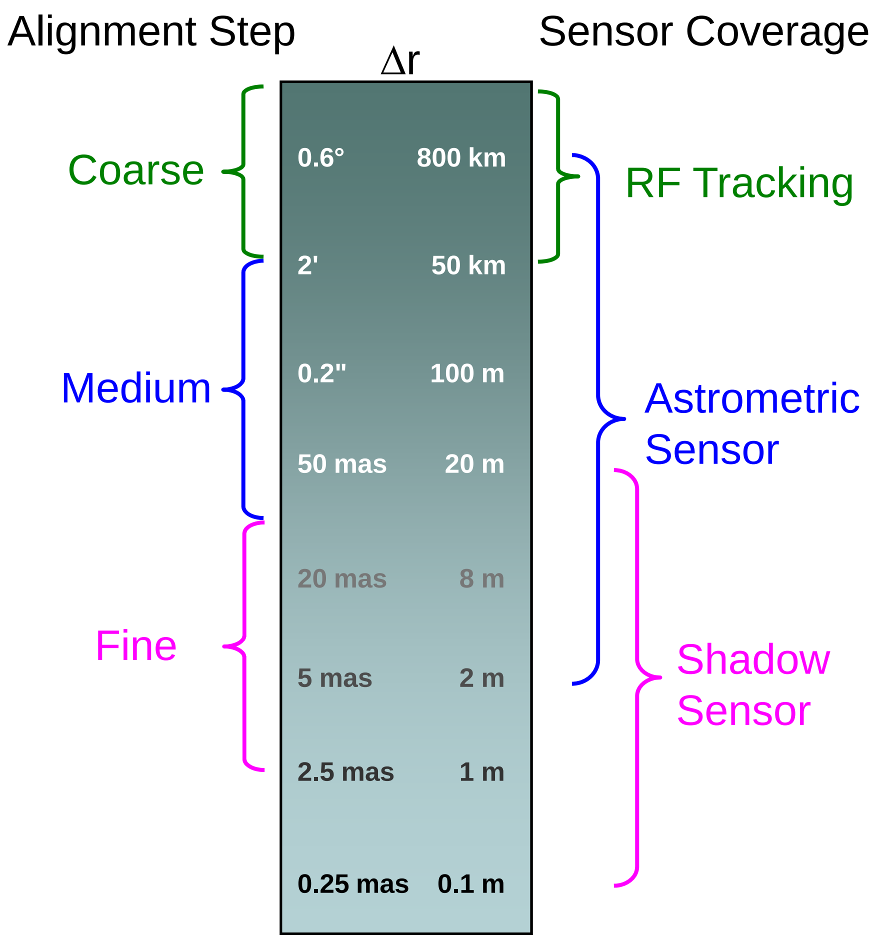
- Starshade diameter (4a) =25 m
- Starshade separation (z) =15,000 km



P=16 → very large formation-flying box

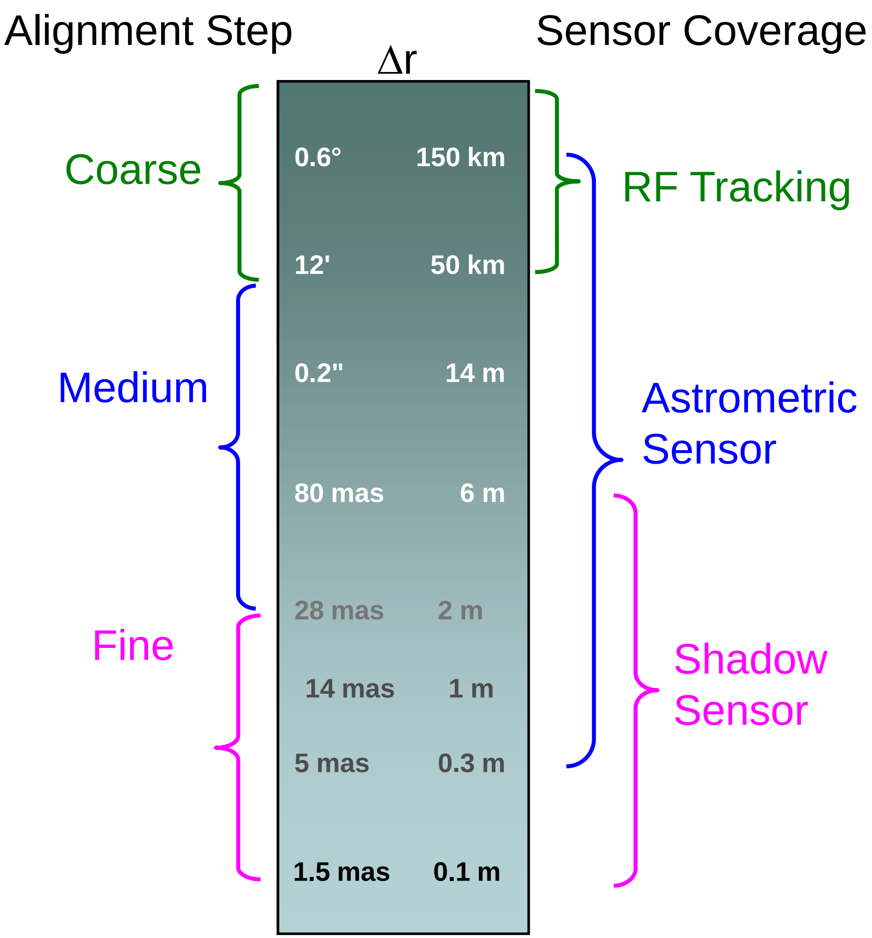
TAC System Limits for Original NWO Design

- Snapshot of the capabilities of the alignment sensors and the handoffs for the NWO TAC system
- A robust system with large spatial and angular overlaps between the control and sensing capabilities at each step
- A backup system consisting of beacons provides failure support
- During the first few alignment maneuvers, we expect many hours to days for the medium alignment step
- With experience, this alignment step should be down to a few hours, with very little telescope time until the end of the phase



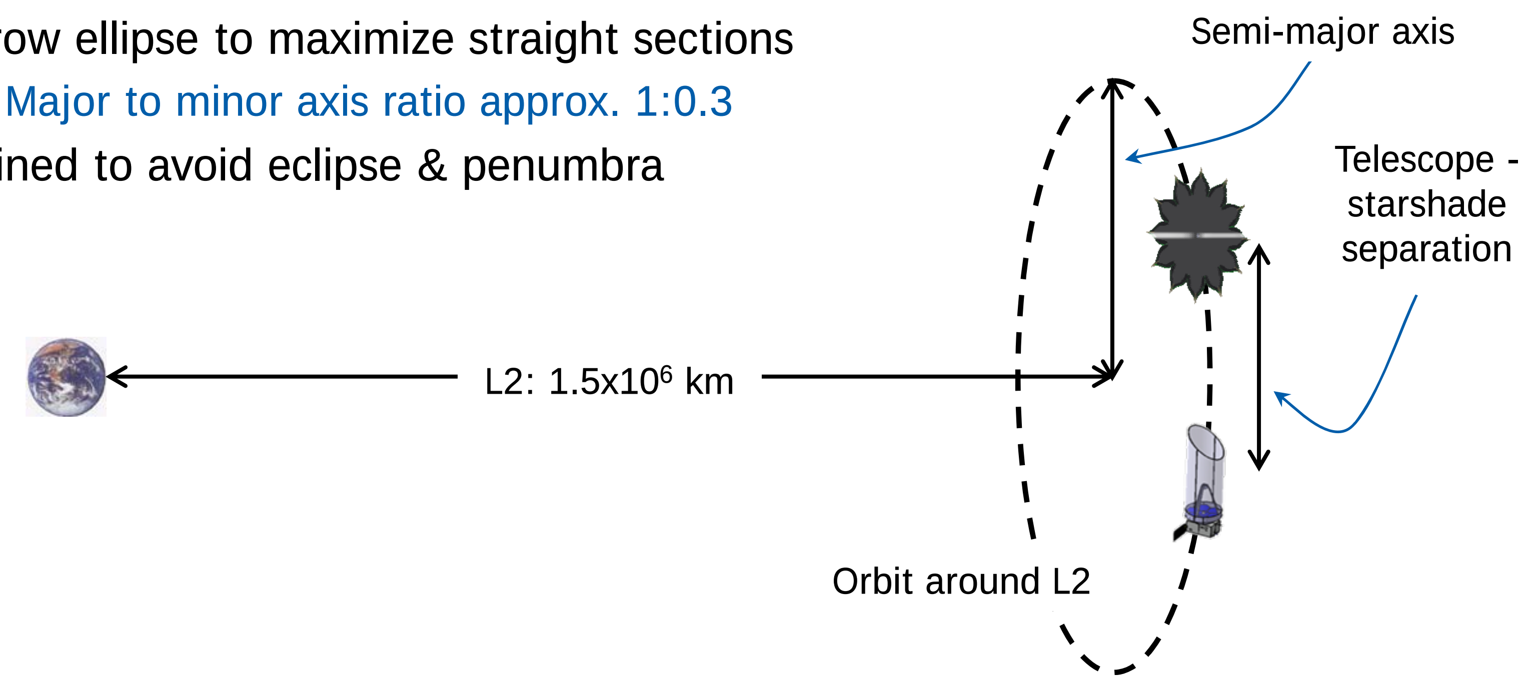
TAC System Limits for ACCESS Design

- Rough snapshot of the capabilities of the alignment sensors and the handoffs for the ACCESS + Starshade TAC system
- The same angle corresponds to a larger physical scale due to 15,000 km separation
- Fine alignment requirement is relaxed to ±2m (alternatively can use fewer petals)
- Astrometric sensor accuracy of 4-5 mas should be enough to do fine alignment step, especially with larger box size. **Could eliminate the need to add a Shadow Sensor to the telescope.**



Set top level limits on orbits and permissible telescope-starshade separation

- A family of solutions exists for orbits around L2
  - L2 orbits require ~5 m/s of ΔV per year to maintain the orbit
- Ideal starshade orbits start at orbits with semi-major axis much larger than the starshade-telescope separation
- For large starshade separation, orbits should be:
  - narrow ellipse to maximize straight sections
    - Major to minor axis ratio approx. 1:0.3
  - Inclined to avoid eclipse & penumbra



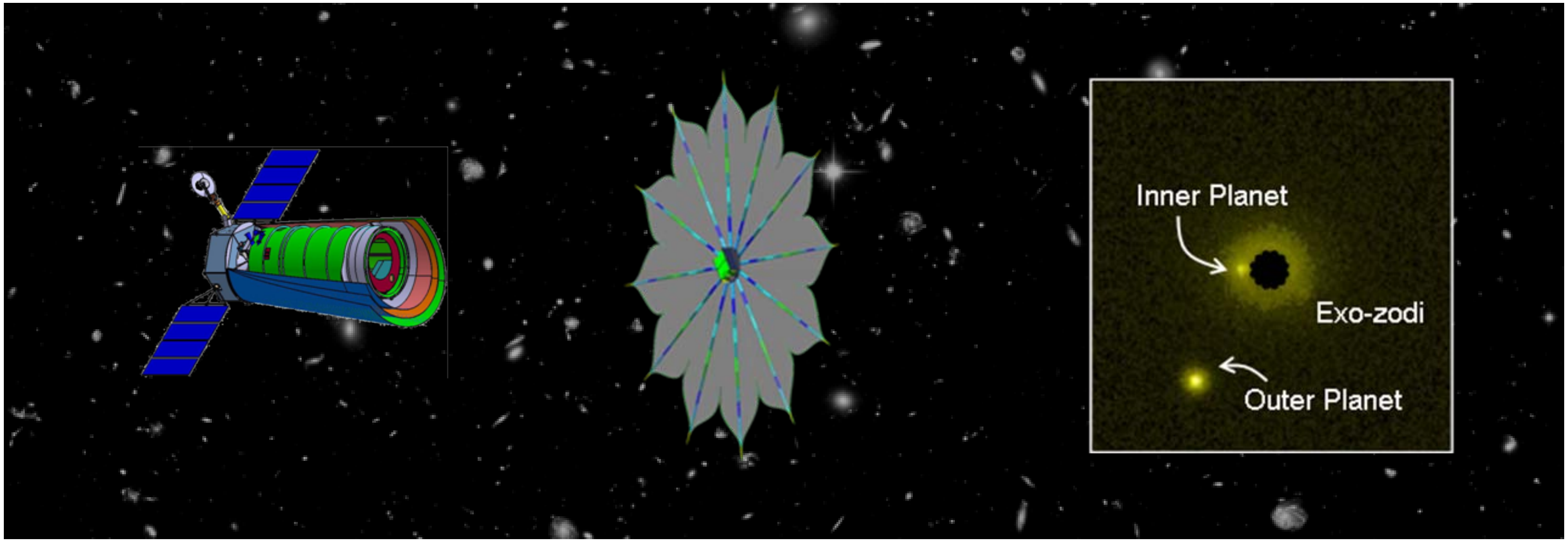
ACCESS Orbital Limits

- The ACCESS starshade has a separation of ~15,000 km
- Orbital limits
  - Semi-major axis should be ~400,000 km or larger
  - Semi-major axis should be ~900,000 km or smaller
  - **Ideal size between 600,000 km to 800,000 km**
- Larger orbits:
  - Require more fuel for stationkeeping
  - Stationkeeping error increases risk of rapid deorbit (kick out)
- Smaller orbits:
  - May incur eclipses and penumbra shadowing
  - Significantly limit FOV and look direction
  - Significantly limit usable portion of the orbit

Backup Charts

Why Starshades?

ACCESS + Starshade ⇒ Debris Disks & Extrasolar Planets



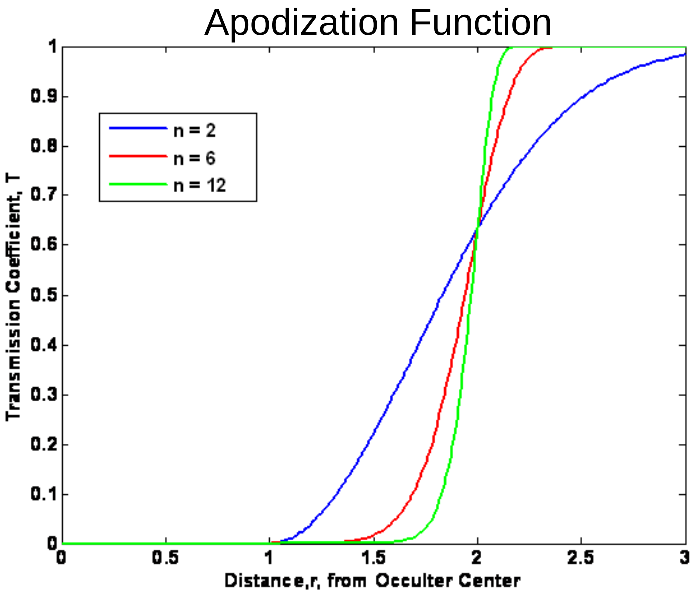
Starshades are Feasible

- Apodized Starshade

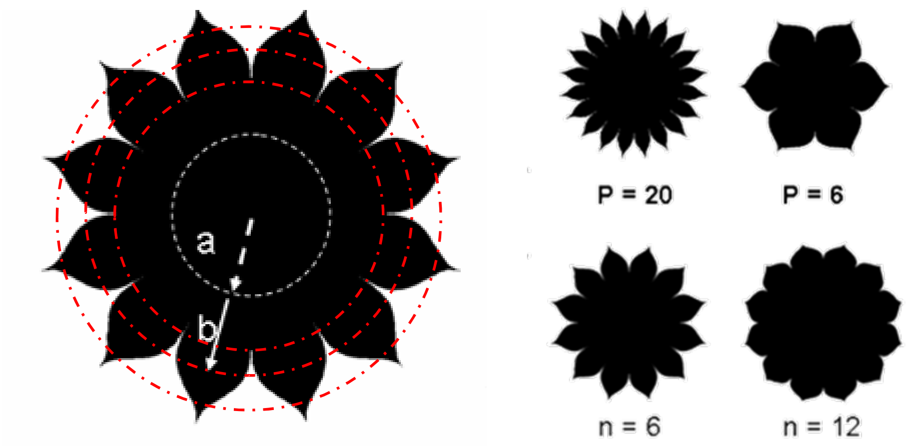
Webster Cash's Hypergaussian function

$$T(r) = 0 \qquad r < a$$

$$T(r) = 1 - \exp\left(-\left[\frac{r-a}{b}\right]^n\right) \qquad r > a$$



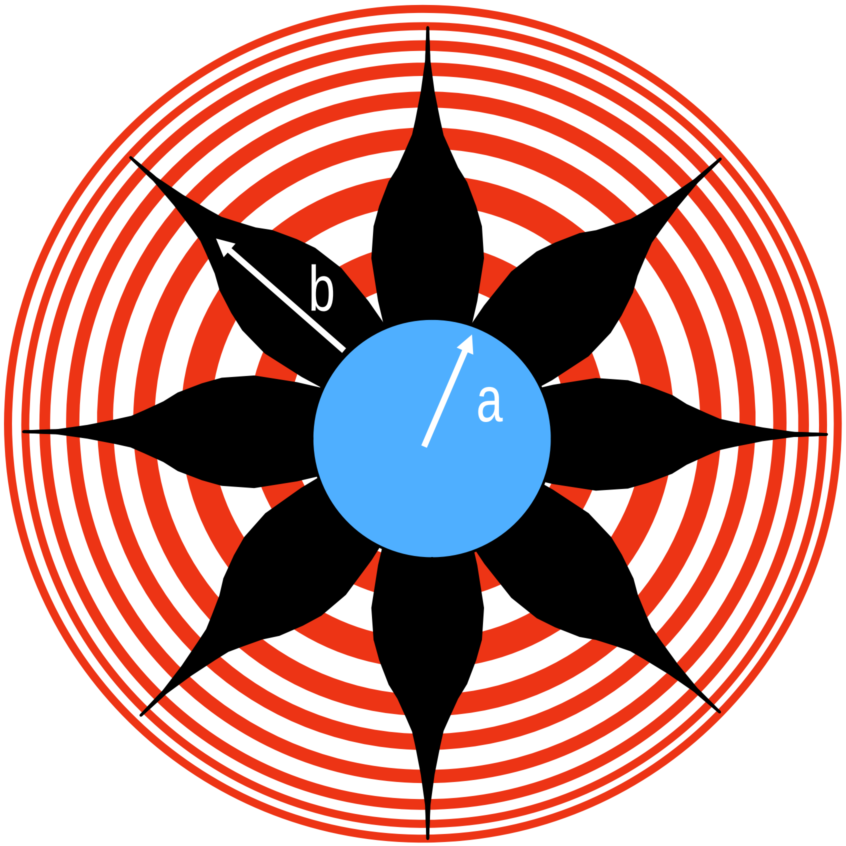
- Binary Apodization



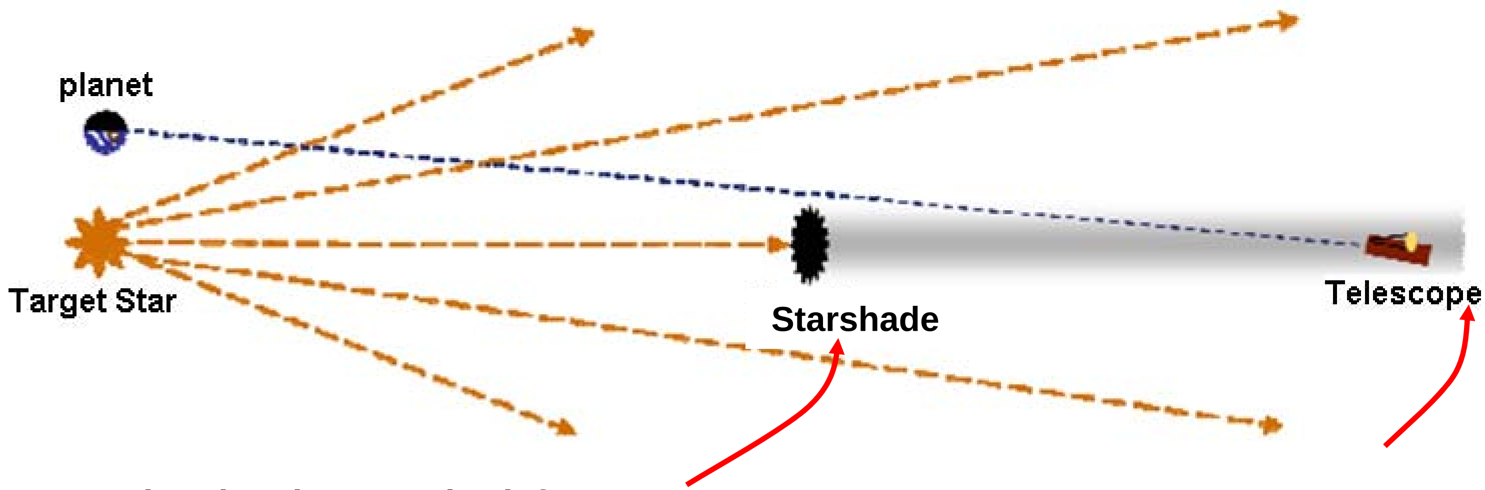
Azimuthal sum of fraction of opaque to transparent area conforms to apodization function

Starshades Provide High Contrast

- Key to making a dark (10^{10}) shadow is precise control of the diffraction of light from the edges of the occulter
  - Previous attempts at occulters had different lower performing solutions
- Hypergaussian shape is a quantum leap forward in this area
- The shape is carefully designed to cause the diffracted light to destructively interfere, giving a dark, abprut shadow, very much like a geometric shadow
- Petal shape is exponential in width ~$\exp(-(a/b)^n)$
  - b is 1/e scale of petal shape
  - n is an index of petal shape
  - a is the radius of the central circle



Starshade Architecture is Flexible



- Starshade decoupled from Telescope
  - Relaxes requirements on telescope
  - Starshade can be replaced by subsequent launches
  - Different sized Starshades may be launched to perform different functions
    - Planet searches, stellar disk characterization, exo-zodiacal dust mapping
- Many choices for Telescope
  - Can work with existing telescope: JWST, SOFIA
  - Can work with dedicated telescope:
    - Telescope can be tailored for other purposes
  - Telescope can be designed for long lifetime (>20 years)

Starshade Has Little Impact On Telescope

- Need cooperative Trajectory and Alignment Control (TAC) system
  - Beacons and sensors located on the telescope
  - Use the focal plane to help with alignment
  - During an observation, telescope needs to communicate with starshade
- Observation/Operations cadence with telescope need to be carefully coordinated to maximize science return.
- Depending on desired viewing geometry, telescope may need large baffle to enable observation at small sun angles (~50 degrees)
- Little to no impact on telescope optical design
  - Ultimate IWA depends on telescope PSF (starshade residual convolved with PSF to get planet contrast capability at the detector)
  - No thermal or mechanical design impacts other than required for TAC system

Starshades Can Observe Many Targets

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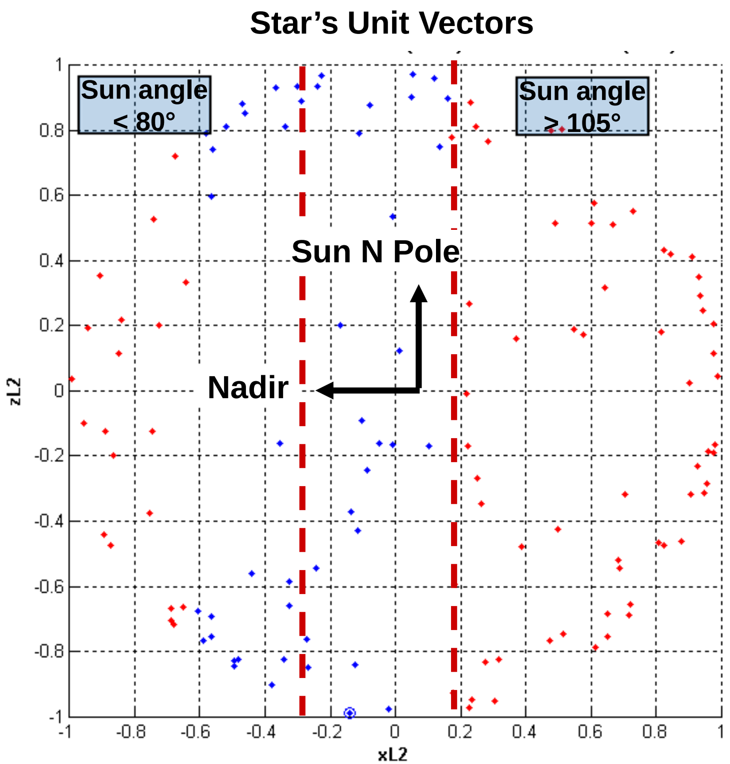
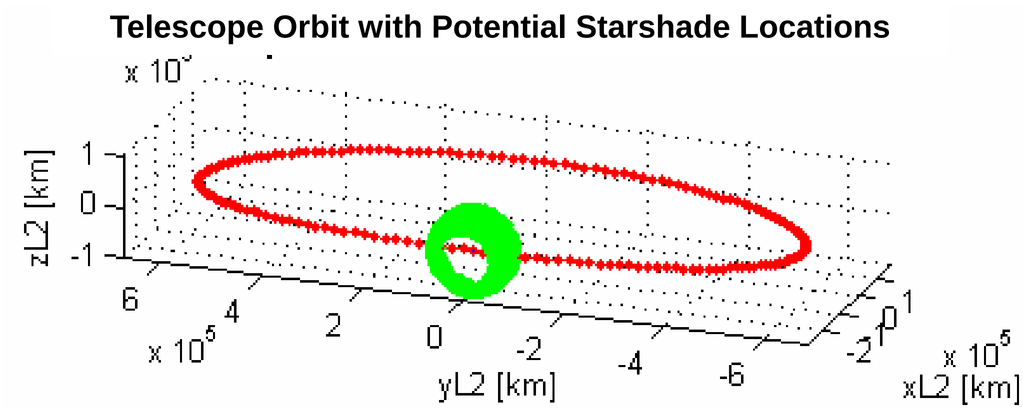
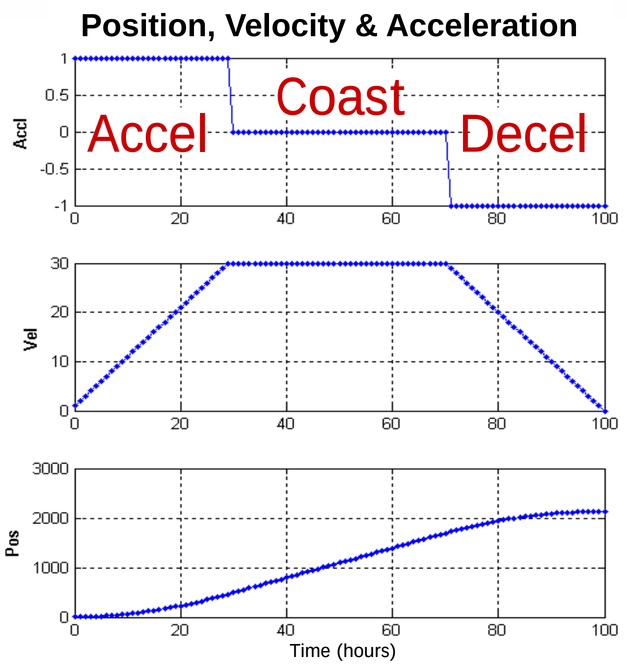




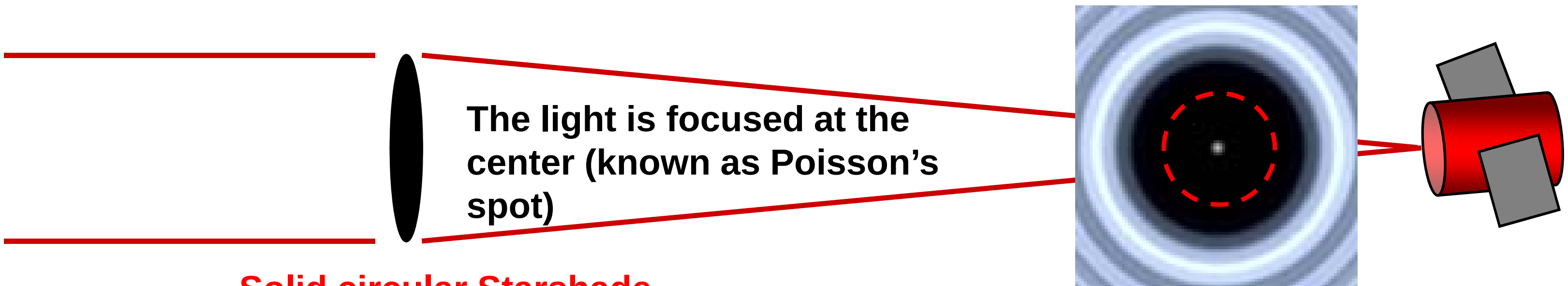


- Instantaneously viewable sky (β = 80° to 105°)
- Approximately 1/4 of 131 Turnbull list stars visible at once

Starshades Operate in the Fresnel Regime

Diffraction around a solid circle

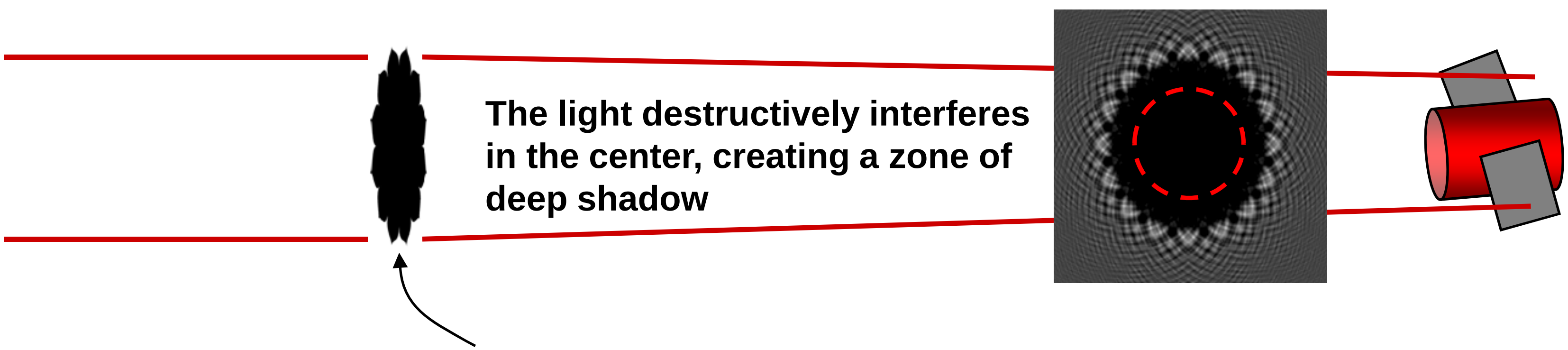
Telescope flies in the shadow



Solid circular Starshade

http://daugerresearch.com/fresnel/PoissonAragoStory.shtml

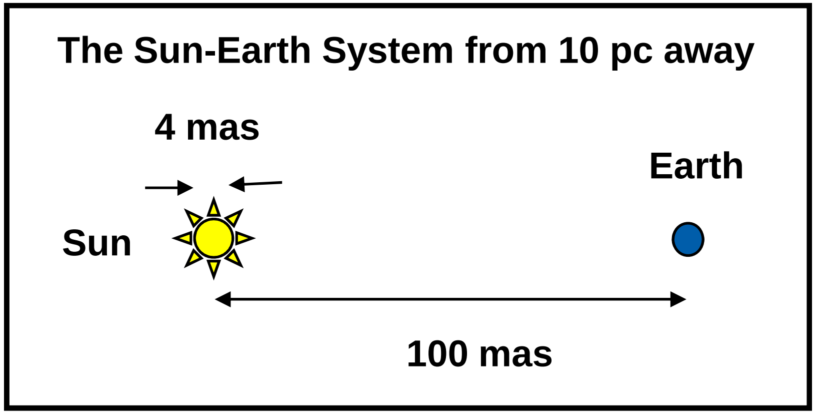
Diffraction around an "apodized" Starshade



Special petals shaped to cause destructive interference in the optical near field

Resolving the Central Star is Difficult

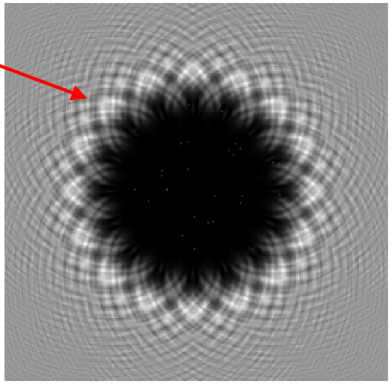
- To resolve our Sun at 10 pc, we need telescope diameter ~38 meters
  - Prohibitive with current technology
- To resolve the Earth around the Sun at 10 pc, telescope diameter ~ 1.5 meters
  - Need to extinguish the central sunlight so the dim Earth can be visible
- Terrestrial planets shine by reflected light
  - Earth albedo ~30%, the intensity difference between the Sun and Earth is 1.4×10^{-10}



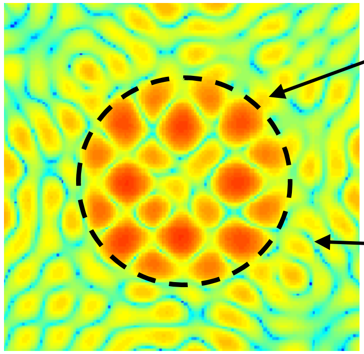
Starshade Optical Performance

Starshade Shadow Depth Simulation

Petal edge interference pattern



Starshade Point Spread Function

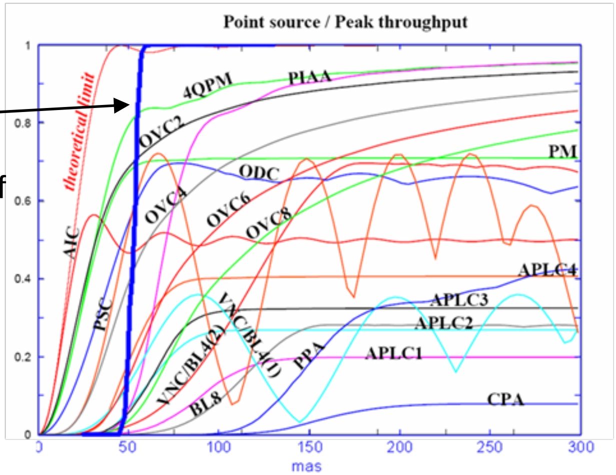


Inner working angle

Residual starlight + simulation noise

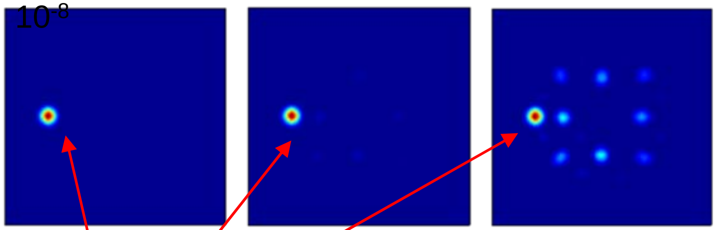
Starshade vs. Coronagraphs

Thick blue line indicates the performance of a 25 m Starshade



Planet Detectability

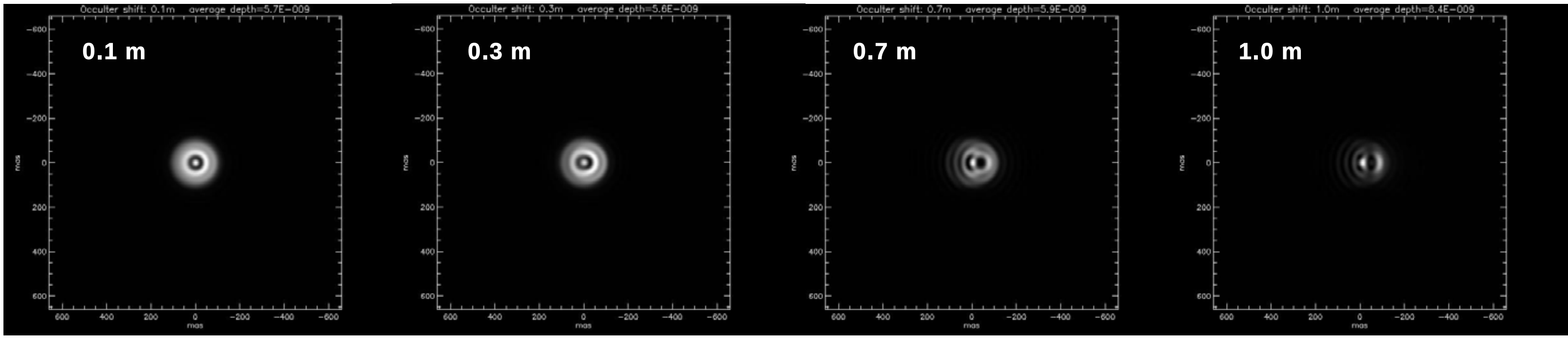
Contrast = 10^{-10} 10^{-9} 10^{-8}



Simulated terrestrial planet

PSF Distortion Due to Errors

- As starshade moves off axis, the PSF becomes distorted



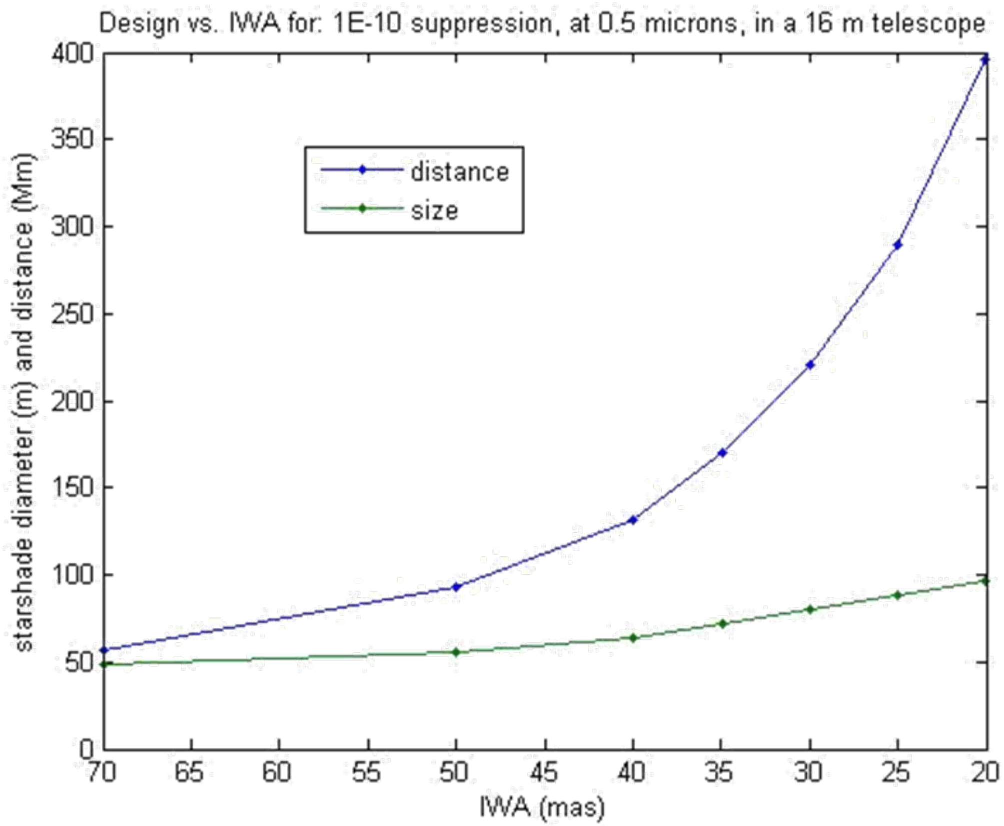
- This will occur with other classes of errors, e.g. starshade shape distortion
- Designs that are sensitive to asymmetry will need much tighter alignment requirements and tighter tolerances
- Our Starshade baseline design easily tolerates these errors

Suppression vs. Contrast

- We have designed for 10^{-10} suppression in the aperture plane
- Due to convolution with the telescope PSF, the contrast at the location of a potential exoplanet (well outside the IWA) will be at least 30x lower
- Suppression value of 1×10^{-10} translates to contrast of 3×10^{-11} in the pupil plane

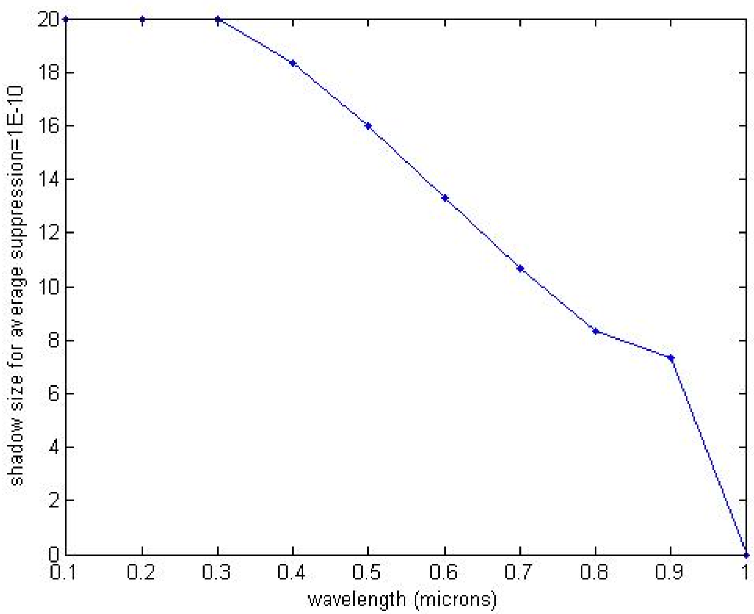
Flexible Design Accommodates Science Goals

- We can design the starshade for a variety of IWA, contrast, and telescope apertures
- Here is a snapshot of the starshade diameter vs. the desired IWA



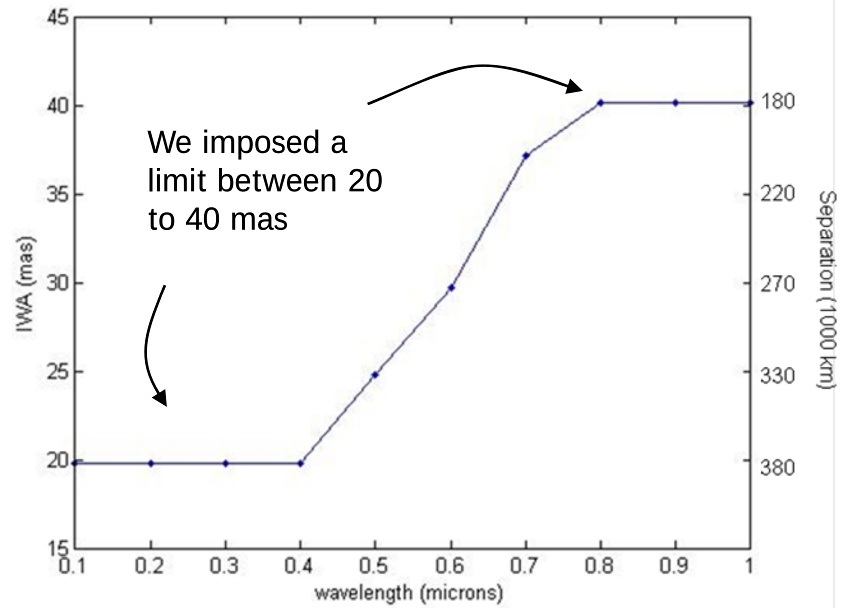
Starshades can be designed for a variety of science requirements

Starshades are Flexible In Orbit



Starshades produce very high suppression in the blue and UV wavelengths

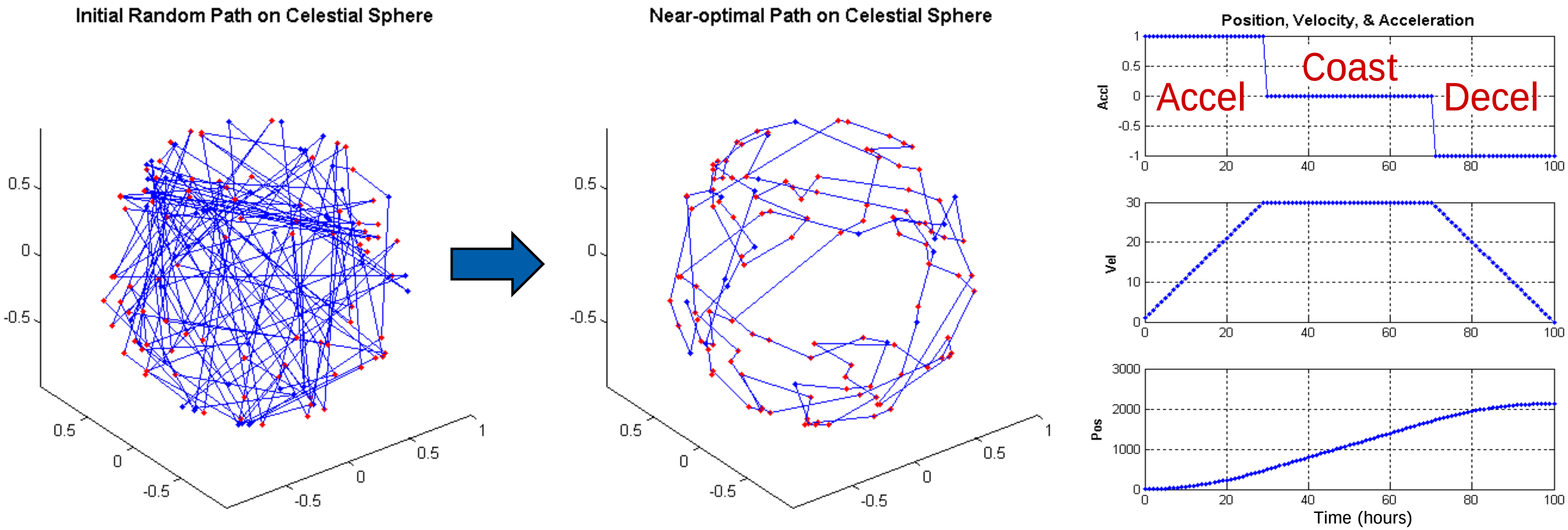
Shadow size is a function of wavelength, which can lead to smaller IWA for short wavelengths, by moving starshades farther away



IWA & Contrast can be Adjusted In Orbit to Respond to target star characteristics

Mission Planner to Generate Best Path

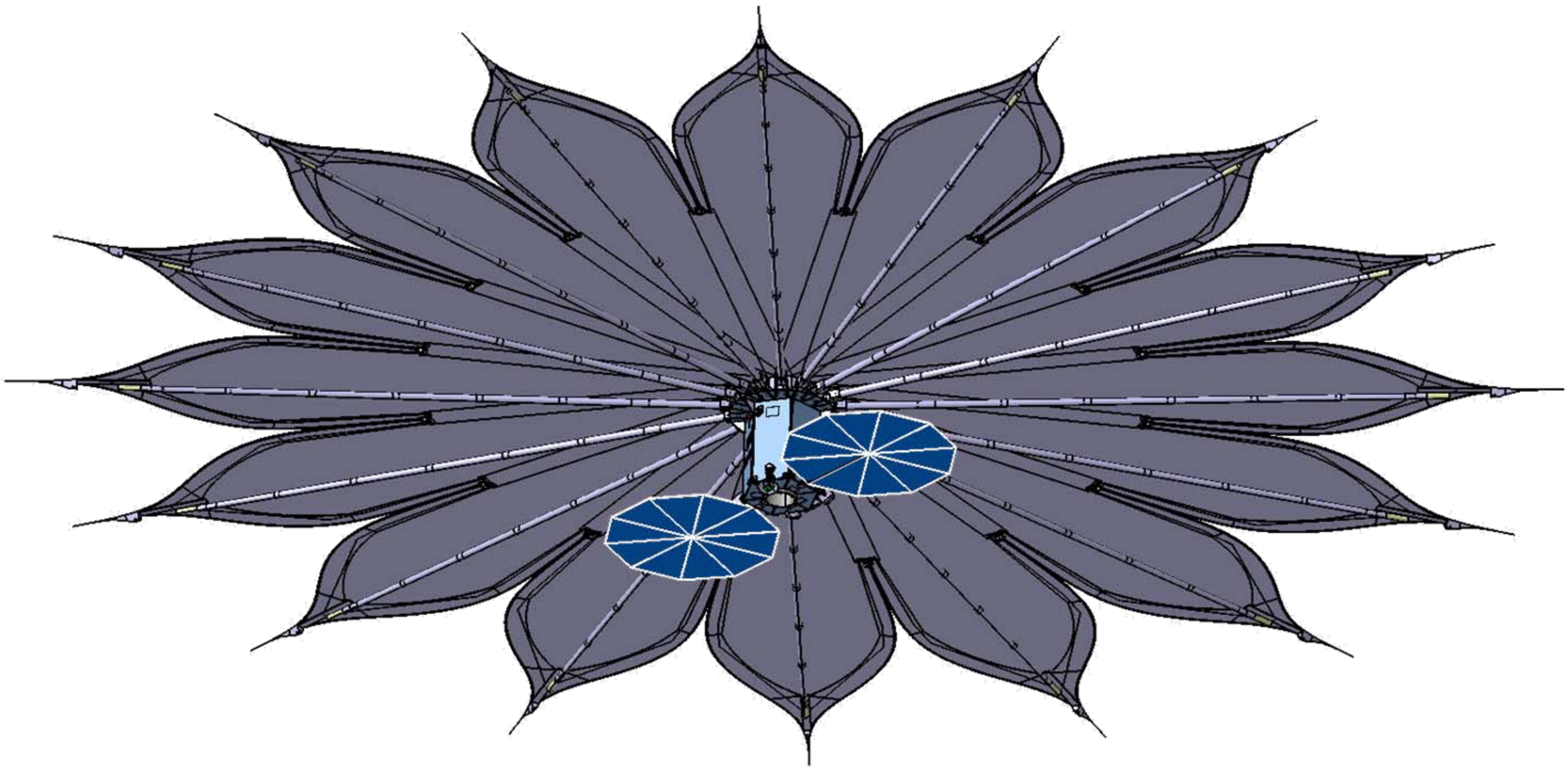
- Completeness = probability of finding a planet in the HZ around the star if $\eta_{Earth}=1$
- We are in the process of developing a mission planner to optimize the DRM



- For ACCESS, we assume search is finished, and starshade used for characterization
  - Possible science includes atmospheric compsition analysis with R ~3000 spectra, surface terrain deconvolution mapping with high S/N photon variation counts, cloud coverage statistics

Starshade Baseline: “Blooming Onion”

Starshade Design: Dean Dailey (NGAS)



Preliminary Mass Rack Up

NORTHROP GRUMMAN

- CBE mass rack up, with 30% contingency, baseline 25 targets/year

Starshade (25m)	MASS	
Component Description	Total Mass w/out Cont (kg)	Total Mass w/ Cont (kg)
PAYLOAD	579.8	753.7
Astrometric Sensor (AS)	79.8	103.7
Star Shade	500.0	650.0
SPACECRAFT BUS	1264.1	1643.4
SPACE VEHICLE DRY MASS (KG)	1843.9	2397.1
PROPELLANT MASS - Xenon (KG)	580	580.0
PROPELLANT MASS - Biprop (KG)	210	210.0
TOTAL WET MASS (KG)	2634	3187.1

- The ACCESS shade is easily accommodated inside an Atlas V launch vehicle
  - Compaction ratio is less than the NWO flagship class mission
  - There is excess mass margin
- We need to do more work to refine the equipment list and budgets, this is a first order estimate using scaling relationships from the 50m class starshade

NORTHROP GRUMMAN

DEFINING THE FUTURE

New Worlds Observer
Astrophysics Strategic Mission Concept Study
April 24, 2009

APPENDIX Q.3

STARSHADE USE WITH THE JAMES WEBB SPACE TELESCOPE

This appendix is the NWO team's response to the Astro2010 RFI for activities submitted on April 1, 2009. It describes how a starshade, substantially similar to the one designed for the full NWO mission could be flown to L2 to rendezvous with JWST. With no significant changes to JWST, it would become possible to find Earth-like planets and capture spectra of them. By using an existing telescope, the cost of the mission drops into the medium-class range.

Astro2010 PPP RFI Response

The New Worlds Probe: A Starshade with JWST

Contacting Author: Webster Cash
University of Colorado, Boulder
email: webster.cash@colorado.edu
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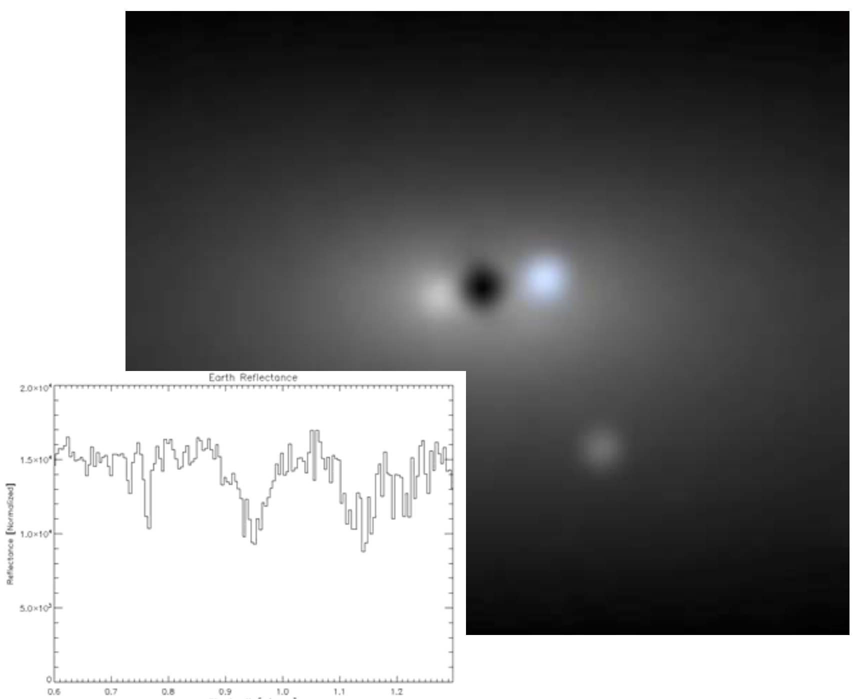
**NWP can do imaging and spectroscopy of terrestrial planets as early as 2016
This may be the fastest and most affordable path to the discovery of life.**

Co-Authors

David Spergel	Princeton University
Remi Soummer	Space Telescope Science Institute
Matt Mountain	Space Telescope Science Institute
Kate Hartman	Goddard Space Flight Center
Ron Polidan	Northrop Grumman Corporation
Tiffany Glassman	Northrop Grumman Corporation
Amy Lo	Northrop Grumman Corporation



I. SUMMARY

The James Webb Space Telescope will be an extraordinary observatory, providing a huge range of exciting new astrophysics results. But it will not be able to directly observe planets in the Habitable Zone of nearby stars – perhaps the most important and tantalizing astronomy goal for the coming decade. In this paper, we discuss the New Worlds Probe (NWP), a concept whereby we send an external occulter, known as a starshade, on its own spacecraft to work in alignment with JWST, enabling JWST to reveal those elusive habitable planets and open the search for life (Fig. 1).

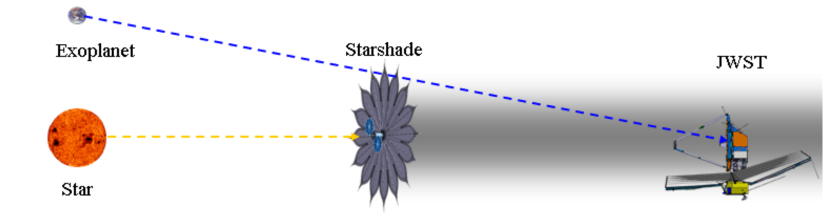


Figure 1: NWO's cost-effective starshade shadows the telescope from the star, while light from a terrestrial exoplanet passes the edge of the starshade unimpeded.

Recent advances in apodization functions have now enabled external occulters to be designed in a practical way for the direct detection of Earth-like planets (Cash, 2006). A starshade approximately 50 m in diameter, flying 55,000 km from a telescope can throw a sufficiently deep shadow over a telescope to reveal Earth-like planets at 10^{10} suppression, at as little as 75 milliarcseconds (mas) from the parent star. NWP will image planets from the habitable zones outward around nearby stars and immediately capture spectra to determine their natures. The search for water planets will be possible using the strong water absorption bands in the near infrared. Biomarkers like the O_2 line can be detected with sufficient observing time and can open a serious search for simple life.

The authors of this whitepaper are completing two Astrophysics Strategic Mission Concept Studies called the New Worlds Observer and THEIA. Both groups concluded that starshades working with a 4 m-class UV/Optical/near-IR telescope would enable detailed study of Earth-like planets at the price of a flagship mission. The teams joined with the Space Telescope Science Institute to discuss the faster, less expensive option of a starshade being used with an existing telescope, JWST. The NWP program can be executed quickly and efficiently for the price of a medium (or Probe) class Exoplanet mission. The starshade can be launched up to 3 years after JWST and rendezvous with the telescope in orbit around L2 (Fig. 2). The starshade structure was designed using high-heritage components – integrated development of NWP could start today. NASA can image terrestrial planets by 2016.

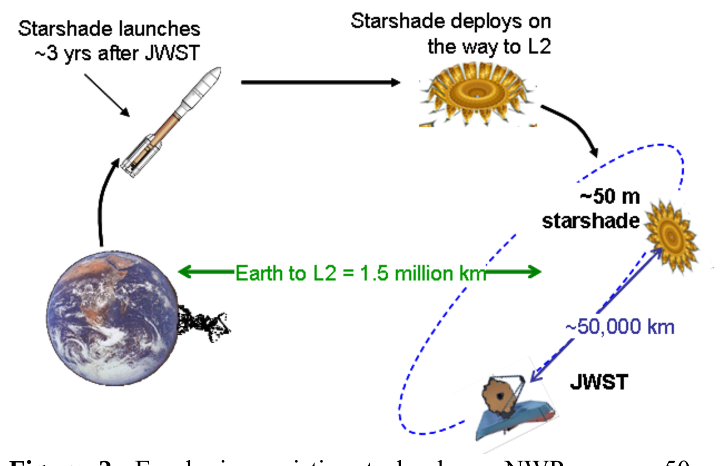


Figure 2: Employing existing technology, NWP uses a 50 m starshade with JWST to image and characterize extrasolar planets.

II. KEY SCIENCE GOALS

NWP is the fastest and cheapest way to make progress on many of NASA's grand themes, such as finding planetary systems like our own and discovering life in the universe. With current and near-term technologies, we can make great strides in finding and characterizing planets around nearby stars. By the middle of the next decade, NWP will enable us to find terrestrial planets around other stars and determine their habitability. This is a valuable addition to JWST's science program.

The science program of NWP uses the extensive capabilities of JWST's instruments. We assume a total available exposure time for the starshade of 7-9% of the total exposure time on JWST (or 10^7 sec for a 5 year mission). This time budget is smaller than the typical amount available for a dedicated mission like NWO or THEIA and the science goals are designed to make optimal use of this time by balancing the characterization of known objects with a reasonable survey of nearby stars. The key science goals for this mission are:

1. Find Terrestrial Planets: survey nearby stars for Earth-like planets to a completeness = 10.
2. Characterize Terrestrial Planet Habitability: conduct spectroscopic analysis on the planets found, searching specifically for water and determining the planets' temperature. Deeper spectroscopy can then be used to search for more challenging species such as oxygen.
3. Characterize Known RV Planets: find the size, temperature, and atmospheric composition of known radial velocity (RV) planets. These include mostly giant planets (Jupiter to Neptune mass) and potentially super Earths by the NWP launch date.
4. Characterize Exozodiacal and Debris Disks: determine the brightness, structure, and composition of exozodiacal and debris disks.

The starshade's starlight suppression works better at shorter wavelengths for a given starshade size. In the optimization of a starshade (Cash et al. 2006; Vanderbei et al. 2007) for JWST, the main requirement driving the design is starlight suppression at the longest wavelength. The increasing size of the starshade with increasing longest wavelength must be balanced with the need to maintain a reasonable starshade size. The operating wavelengths chosen for flagship missions such as NWO and THEIA are ~0.4 to ~1.1 μm and ~0.25 to ~1.1 μm, respectively. JWST is optimized to work in the near- to mid-IR (λ>0.6 μm). This provides access to an oxygen band (0.76 μm) and offers the advantage of expanding the sensitivity to the near-IR, which is a rich area for exoplanet science (TPF STDT report).

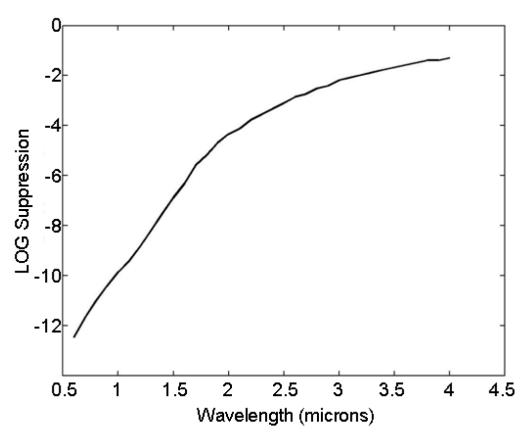


Figure 3: Starlight suppression with the NWP starshade versus wavelength for a spacecraft separation of 55,000 km.

Fig. 3 shows an example of starlight suppression at the JWST aperture versus wavelength for a 50 m starshade operating 55,000 km from JWST, which provides an IWA of 75 mas. We can adjust the separation between the starshade and telescope while on orbit to select the optimal performance. For example, at a distance of 40,000 km, the IWA increases to ~100 mas, but the starlight suppression at long wavelengths improves to

~10^{10} at 1.5 μm and ~10^{8} at 2 μm.

1) Find Terrestrial Planets

The detection of terrestrial planets by NWP is done using imaging with NIRCam on JWST at the shortest wavelengths. The filters of interest are the F070W, F090W, and F115W bands, covering 0.6-0.8 μm, 0.8-1 μm, and 1-1.3 μm, respectively. In addition, there are a number of medium band filters that can be used (F140M, F162M, F182M, and F210M) with applications for the detection of water vapor or methane absorption bands.

We can detect an M = 30 point source at S/N=10 with both the F070W and F090W filters in ~66 hours given a exozodiacal background equal to our own (see below). This will take ~34 hours with the F070W filter and ~22 hours with the F090W filter. Detecting planets against the exozodiacal background lengthens the exposure, though advanced signal extraction can help mitigate this problem. One of the difficulties is that the JWST PSF is significantly undersampled at these wavelengths.

In any single observation of a planetary system there is a probability that a planet will be detected. For example, the planet could be in transit and hidden behind the shade. Or, it might be at quadrature and easy to see. In the upper diagram of Fig. 4, we show probability contours for the single visit discovery of a planet as a function of its mass and distance from the star for the case of 10 pc. NWP will have probability of planet detection in the 20-50% range for planets in the habitable zone and larger planets, farther out, can have probabilities of discovery in excess of 70%. The lower diagram shows the probability of finding Jupiter-sized planets as a function of semi-major axis. The NWP system will have better performance that shown in the plots due to a smaller system IWA.

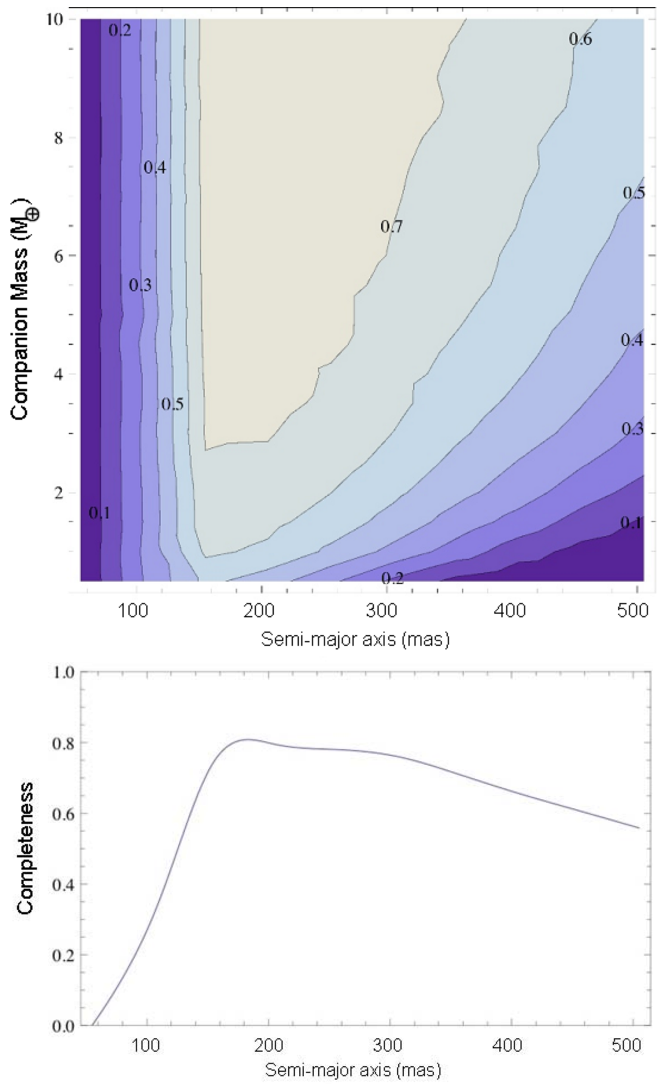


Figure 4: Top: The completeness (discovery probability) contours for a single-visit completeness of planets around a solar-type star at 10 pc. The contrast limit is Δm = 26, with a conservative 100mas IWA. **Bottom**: a slice of the contour for Jupiter mass planets.

2) Characterize Terrestrial-Planet Habitability

Photometry and spectroscopy will reveal the true nature of these planets and the systems in which they were born. Spectroscopy of terrestrial exoplanets will quickly reveal a wealth of information about the planet's atmospheric and surface conditions, most notable the detection of water which can be seen even in fairly low resolution spectra. Further characterization may be possible in the most favorable cases including the search for oxygen and a number of other species that could potentially be detected in the near infrared (e.g., carbon dioxide, methane, or ammonia). Spectroscopy of giant planets at a resolution comparable to what is nowadays achieved on brown dwarfs will constrain the surface gravity of these objects and open the possibility of a complete characterization including mass, temperature, radius, and major atmospheric absorbers.

We have calculated the exposure times needed to get an S/N=10 spectrum of an Earth twin and of giant planets at 10 pc. We will use the prism in NIRSpec to get low-resolution spectra (R~40) and the gratings to get high-resolution spectra (R=1000 or 2700). The high-resolution spectra can be binned down to get R~100 spectra of terrestrial planets at the cost of additional detector noise. This results in observations with the grating being detector limited while observations with the prism are background limited.

Spectra of an Earth-like planet at 10 pc obtained with NIRSpec and NWP is shown in Fig. 5. The strong absorption features of water, indicative of oceans and clouds, are readily detectable even in the low-resolution spectra. More exciting is the presence of biomarkers such as absorption lines from molecular oxygen in the higher-resolution spectra. These features are in the spectrum of the Earth solely as a byproduct of plant life.

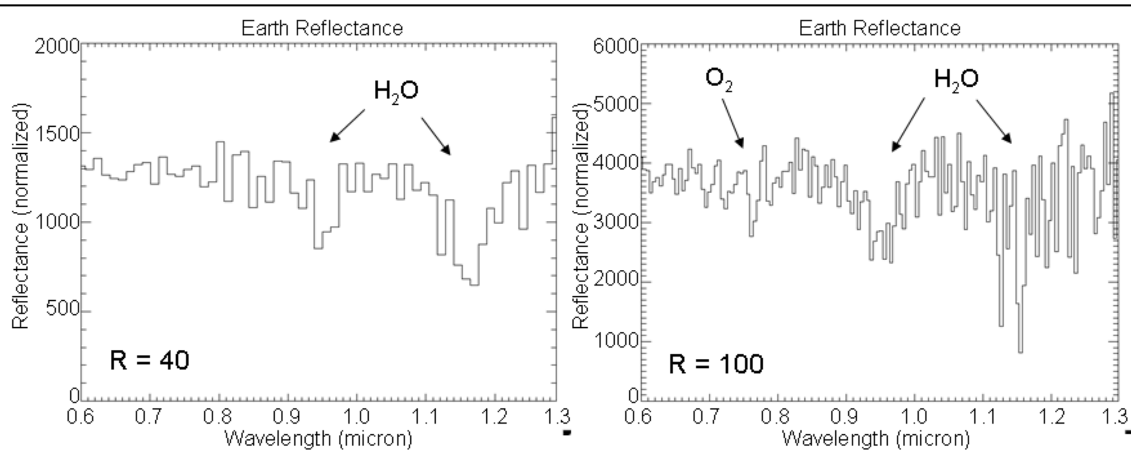


Figure 5: Simulation of the Earth spectrum with NWP and NIRSpec. Left, resolution of R=40 with the prism in (10^5 sec). Right: R=100 obtained with R=1000 grating in $1x10^6$ sec. The water bands are easily detectable in a low-resolution spectrum and would give the proof of existence of a habitable planet. The oxygen A band is detectable in the R=100 spectrum in a reasonable amount of time with S/N<10 in the continuum.

For a terrestrial planet at 10 pc, we estimate the time to get an R=40 spectrum with the prism is 10^5 sec, assuming an exozodical dust level of equivalent to that in our Solar System and a slit width of 0.1″ with the Integral Field Unit (IFU). This calculation includes an additional 1 zodi of background to account for scattered-light contamination. The observation is background-limited and the exposure time doubles with the long slit of width 0.2″. The oxygen line cannot be seen in the R ~ 40 spectra due to spectral line confusion, and is not a function of S/N. The same amount of time will be necessary to obtain an R=1000 spectrum of a Jupiter analog or an R=2700 spectrum of a more massive giant planet. A spectrum of an Earth-like planet using the

R=1000 grating (1.0-1.8 μm) and binning down to R=100 can be obtained with S/N ~5 in 10^6 sec, making the crucial oxygen A band visible.

Using the Integral Field Unit (IFU) or the micro-shutter array (MSA), it is potentially possible to simultaneously obtain spectra of several planets. The IFU provides a 3″ × 3″ field of view with spatial resolution of 0.1″. This will be particularly interesting for multiple-planet systems and interplanetary dust. However, slit and MSA spectroscopy have higher efficiency than the IFU and would be preferable for the faintest targets. MSA spectroscopy can also be used to image multiple objects in the field although the apertures are larger than the IFU (0.2″ x 0.45″).

3) <u>Characterize Known RV Planets</u>

The third goal focuses on the characterization of planets that are already known to exist. As of today, there are 24 giant planets with projected semi-major axes larger than 100 mas (Exoplanet Community Report Chap. 3), many more planets are expected in the coming 5 to 10 years before NWP's launch. This will be a target rich area of discovery. These planets typically have ~10^{-9} contrast and are readily accessible to NWP, both for imaging and spectroscopy. Combining RV and imaging can break the m*sin*i degeneracy and provide the planet's mass. Spectroscopy at R=40 with JWST's NIRSpec prism and even R=1000 is within reach for Jupiter twins, enabling better measurements of surface gravity and atmospheric constituents. With access to giant planet masses, temperatures, gravities, radii, and the main atmospheric absorbers, NWP will open new areas in understanding planet formation and diversity. We will use NIRSpec to get spectra of both the known planets and any additional planets that we may discover in each system.

4) <u>Characterize Exozodi and Disks</u>

NWP's fourth goal is to study exozodiacal dust (or "exozodi") in planetary systems, which is generated by comet and asteroid collisions. Observing exozodi is crucial, both for its science return and as a source of background noise for exoplanet observations. Currently known exozodi disks (better known as debris disks) have L_{IR}/L_* values in the range of 10^{-3} to 10^{-5} (Bryden et al. 2006). The zodiacal dust interior to our asteroid belt has $L_{IR}/L_* \cong 10^{-7}$, which we call 1 "zodi". We are not currently able to detect this amount of dust around other stars; this can only be done with high-contrast direct imaging. Since NWP has no outer working angle and produces zero distortions in the field, exozodiacal light and debris disks will be optimally imaged by this system.

Exozodiacal light also provides a treasure trove of scientific discovery. Just as NASA's Deep Impact mission probed a Solar System comet by studying material generated in a man-made collision, exozodiacal dust provides information on the composition of extrasolar asteroids and comets. Furthermore, the distribution of the exozodi is a sensitive tracer of the system's orbital dynamics. Planetary orbital resonances will be displayed as gaps and enhancements in the dust. Tiny planets, too small to be seen directly, should leave distinct marks. Imaging the exozodi gives us the inclination of the system's ecliptic plane, which can help us make a first estimate of a planet's orbit from a single image.

Zodiacal and exozodiacal dust also create a background flux that is mixed with the planet signal in both images and spectra. Even if nearby systems have exozodi levels no greater than the Solar System level, zodiacal and exozodiacal background will be largest source of noise for most targets, assuming the starlight is suppressed to ~10^{-10}. The surface brightness of the exozodi is the main factor controlling how long it takes to detect an exoplanet buried in it. We know very little about exozodi levels in nearby stellar systems. However, NWP is quite robust against the presence of many zodis of dust in the extrasolar system.

Starshade Red Leak

Although it is possible to optimize the starshade to work for the entire JWST short-wavelength bandpass, the size of the starshade becomes large and the separation between the starshade and JWST becomes too distant. We can use filters to limit the bandpass, but the question of the out-of-band quality of these filters becomes important; on the red side of the band the starshade's suppression drops as the wavelength increases. In the case of NIRCam, the filters have out-of-band rejection of 10^4 to 10^5, which requires a starshade suppression of at least 10^4 to 10^5 over the entire sensitivity band of the NIRCam detector (up to 2.4 μm).

For spectroscopy with NIRSpec, this problem is relaxed because the light is spectrally dispersed. The only concern is long-wavelength light scattered into the short-wavelength pixels. Moreover, any combination of filter and dispersive element is possible and we have identified two useful target acquisition filters: F110W (1.0 to 1.2 μm) and F140X (0.8 to 2.0 μm). The latter is the most interesting for exoplanet science in general, including potential access to the bands of H_20, CH_4, CO_2, O_2 (1.27 μm), CH_4, water ice, and NH_3. However it misses the oxygen A band at 0.76 μm. The current filter has a red leak of ~ 8% at 3 μm which may limit spectroscopic performance for the faintest objects because of scattered light. We suggest an optional upgrade of this filter (see the technology development section below) to improve the out-of-band rejection. Another optional filter modification would be to replace two existing long-pass filters (F070LP and F100LP) with band-pass filters. These filters are intended for use with the gratings in the wavelength range 0.7 to ~1.4 μm and 1 to ~2 μm, respectively, because of combined effect of the grating efficiency and second-order contamination. These filters might be replaced with minimal impact on the JWST science, especially the shorter wavelength filter (F070LP).

III. TECHNIAL OVERVIEW

The Starshade

Recently, Cash (2006) found an apodization function that makes external occulter systems practical with today's technology. The starshade has been realized in the New Worlds Observer mission concept, where a 50m starshade is flown with a dedicated, 4m telescope. Because the starlight does not enter the telescope, there are not particular constraints on the telescope optical quality: the telescope can be on-axis, segmented and even with modest optical quality without significant loss of performance. All these reasons enable the starshade design to work with JWST, even at the shortest wavelengths.

Shown in Fig. 1, the starshade is an opaque screen that flies in the line of sight from JWST to the target star. If the starshade is sufficiently distant it will subtend a small angle to blot out the star while allowing the exoplanet light to pass unobscured over the edge.

Cash's offset hyper-Gaussian apodization function reduces diffraction by many orders of magnitude. A starshade with 2(a+b) = 50 m (the effective diameter), operating ~50,000 km from JWST is capable of 10^{-10} starlight suppression within 75 mas for wavelengths from 0.1 to 1 µm. This starshade has 16 petals, with hypergaussian parameter n = 6. This is essentially the same starshade as the NWO flagship, and so can reuse all the learning and design we have developed for that mission concept.

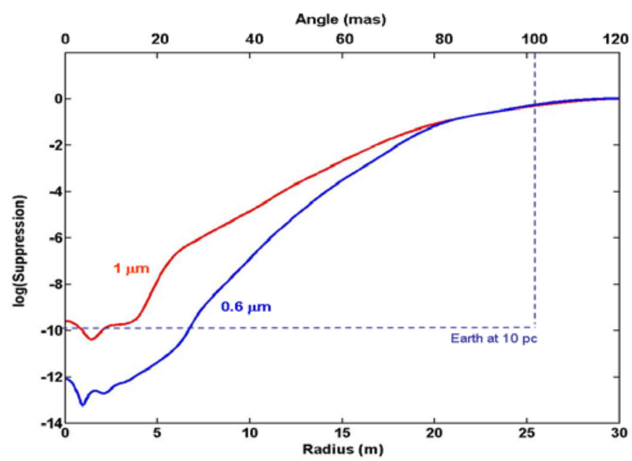


Figure 6: Residual starlight falls by >10 orders of magnitude across a shadow radius of <20 m, allowing observations of planets as close as 75 mas.

Four independent software codes have been developed to simulate starshade performance. Fig. 6 shows the suppression efficiency of the baseline starshade design as a function of both radius and angular offset for two representative wavelengths.

Deriving the requirements and tolerances on the starshade has been a challenge. Never before has anyone set tolerances on an occulting screen that must be understood to the 10 ppm level. In response to this need, two codes were used extensively and cross-checked for agreement and accuracy. One code, written at CalTech under contract to Northrop Grumman Corporation (NGC), is based on a Fourier propagation technique. The other, written at the University of Colorado, relies on an edge integral technique. Via these codes, we have derived more detailed requirements on the starshade shape (Fig. 7), which drive the design of the starshade. The requirements include parameters such as petal number and tip and valley truncation radii. This is one of the key areas that we will continue to mature in the next year.

The starshade payload must be folded up for launch due to its large diameter. NGC, world leader in space deployables, provided the engineering that went into designing a mechanism to reliably deploy the shade and lock it into its final shape. The payload is a passive device that needs to maintain a specified outline. Deployment and shape maintenance of the starshade is one of our technology tall poles and is described in the next section.

The starshade space vehicle baseline design is shown in Fig. 8. The main function of the spacecraft needs to move the starshade from target to target and maintain alignment during observation. The spacecraft is characterized by having a large and very capable propulsion system to provide ΔV for retargeting maneuvers. The NEXT ion propulsion system from Glenn Research Center is used for its high total lifetime fuel throughput and efficiency, enabling the greatest number of targets searched for the least mass. A 16 kW power system is used to provide power to the NEXT system (for comparison, the HST solar arrays are 6 kW). The solar arrays are deployed on a boom which has one axis degree of freedom. Due to solar array shadowing, the travel direction cannot be within 30 degrees of the sun. Fortunately, this happens less than 9% of the time and we carry an extra 3% of fuel to account for the additional travel.

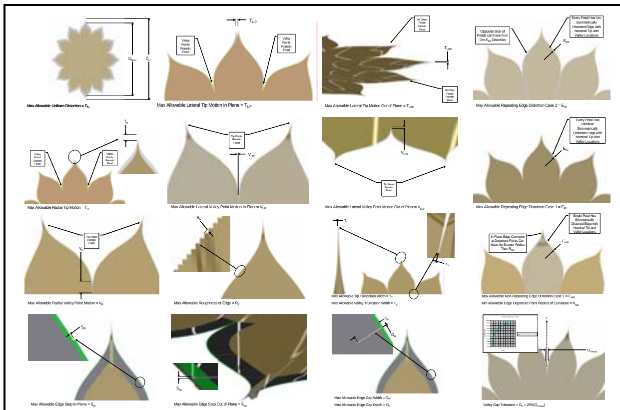


Figure 7: The starshade is tolerant to many distortions. Distortions on the shape of the starshade have been modeled using diffractive simulations and fall within the capability of existing technology.

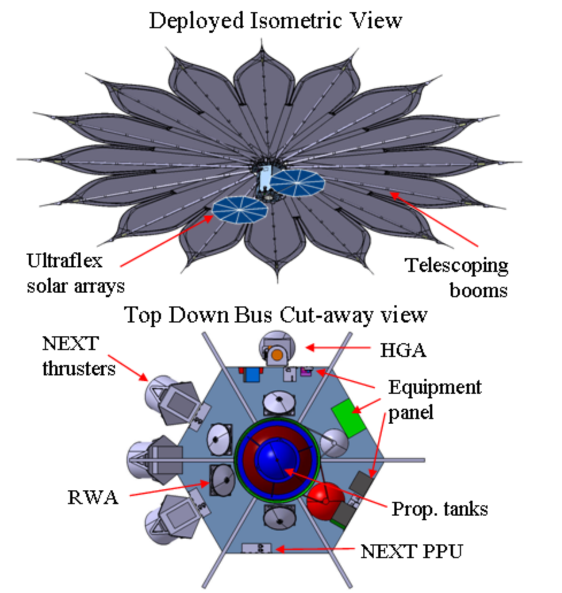


Figure 8: The starshade is a passive payload. The spacecraft bus provides high ΔV with the NEXT electric propulsion system.

Verification and validation of this large deployable is one of the main challenges of NWP. Our top-level plan is to perform unit-wise design and validation, integrated into the technology development process. Starting with the perimeter, for example, we design and validate a tenth-scale rigid edge section to the necessary requirements. We build on the success of this edge test by designing and validating critical edge components such as tips and valleys, and then integrate the pieces by producing to-scale pathfinders of a petal or a quarter section of the starshade, which can be environmentally tested and validated in existing, large thermal vacuum chambers.

JWST

The JWST is a large, infrared-optimized space telescope designed to study the formation of the first stars and galaxies. JWST (Fig. 9) will have a large mirror, 6.5 meters in diameter and a sunshield the size of a tennis court. JWST is being launched in 2013 to the Sun-Earth L2 point, 1.5 million km from the Earth, where it will conduct its observations. The NWP project is primarily concerned with three systems on board JWST: two of the science instruments, NIRCam and NIRSpec, and the sunshield, which reflects sunlight towards the NWP starshade and can be used for an alignment signal.

The NIRCam design consists of two broad- and intermediate-band imaging modules, each with a 2.16' × 2.16' field of view. The modules will have a short and a long wavelength channel, taking images simultaneously with light split by a dichroic at about 2.35μm. The short wavelength channels will be sampled at 4096 × 4096 pixels (0.0317"/pixel), the long wavelength channels by 2048 × 2048 pixels (0.0648"/pixel). The short and long wavelength arms are Nyquist sampled at 2μm and 4μm respectively. NIRCam will also be used for wavefront sensing to assure perfect alignment and shape of the different primary mirror segments. Each imaging module has a pupil wheel with extra optics and pupil analyzers for wavefront sensing. The wavefront sensing capability is fully redundant in both imaging modules because the mission depends critically on its functionality. Although JWST is mainly optimized for the near- and mid-infrared, it has access to shorter wavelengths with modest optical quality down to 0.6~0.7 μm on NIRCam and NIRSpec.

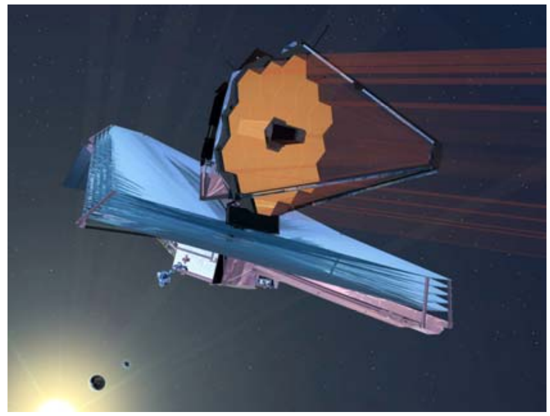


Figure 9: JWST will be able to image and characterize terrestrial planets in 2016 with the addition of the NWP starshade.

In the R~100 and R~1000 modes, NIRSpec provides the ability to obtain simultaneous spectra of more than 100 objects in a >9 sq. arcmin field of view. At R~100, one prism spectrum covers the full 0.7 μm - 5 μm wavelength range. However the resolution is a function of wavelength, and R is about 40 at the shortest wavelengths. At R~1000, three gratings cover the wavelength range from 1μm - 5μm. To improve sensitivity, the pixels will have a larger projected size on the sky (~0.1") than those on NIRCam.

The JWST sunshield is made of five-layers, consists of extremely thin, specially coated, reflective Kapton membranes and a supporting structure, and measures about 22 m × 12 m. The sunshield blocks solar heat, allowing the telescope's science instruments to operate at cryogenic temperatures.

Trajectory and Alignment Control

We will launch the NWP starshade to meet up with JWST in 2016. The launch window is 1 month occurring every 6 months. Fig. 10 shows an example starshade phasing orbit with JWST. It is also possible to rendezvous with JWST on the far side of L2. The launch window would then be 1 month wide, every 3 months, for an additional ~200 m/s of ΔV. Because the separation between the two spacecraft is large, there is no chance of collision even in the case of an error.

The ability of NWP to locate, track, and align itself to JWST is essential for mission success. However, the Trajectory and Alignment Control (TAC) system for NWP cannot rely on a "cooperative" telescope that is able to send data to the starshade; JWST is a passive partner in alignment. The NWP team intends to seamlessly integrate the exoplanet operation into the existing JWST operations architecture which means that the science observations enabled by NWP will be commanded on JWST just like any other observation.

A 50 m starshade, at a separation of 55,000 km from the telescope, must be aligned to the line-of-sight to a target star with a 3σ error of ~2 m in order for the telescope to stay in the deepest part of the shadow. Two meters at 55,000 km corresponds to ~8 mas. In order to achieve 8 mas position control, we must be able to measure the alignment to ~2 mas.

Achieving and maintaining alignment of the starshade and JWST involves major two steps. The first step, coarse alignment, is to move the starshade to within ±50 km of the line of sight from JWST to the target star. During early science operations, this slew can be guided by ground tracking and ephemeris modeling; the starshade will have daily downlinks to the ground, where it performs a position check against ground telemetry, obtains updates on JWST position, and obtains updates (if available) on the JWST visit file. Fifty km is a conservative estimate of the 3-D positional error relative to the commanded position for this technique. Alternatively, we could use a less ground-intensive method suggested by Beckman (2002). By obtaining a ranging measurement, with Doppler data from a ground station, and spacecraft attitude measurements, we can use CelNav (part of GSFC's Enhanced Onboard Navigation System software package) to obtain an accuracy of ±37 km without ground telemetry upload. For routine operations, guidance for this phase can be obtained from the optical astrometric sensor mounted on the starshade.

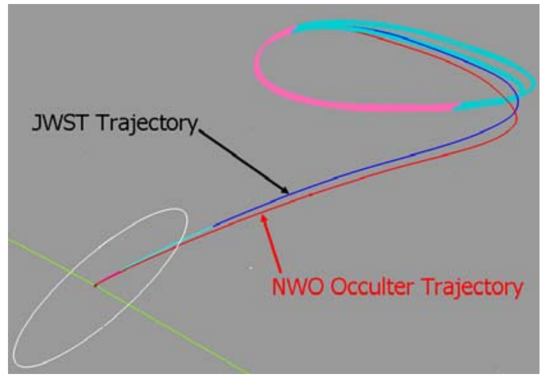


Figure 10: The NWP starshade is launched on a ~100 day trajectory to a position ~50,000 km away from JWST. Exoplanet observations can begin around Oct. 2016.

The astrometric sensor is also the primary source of alignment knowledge for the second, fine alignment step. For the second step of alignment, we use reflected light from the JWST sunshield as the guiding signal for the astrometric sensor (AS) mounted on the starshade. The AS is described in more detail below and each step in the process is outlined in Table 1. We present trades and further work required for the TAC in section IV.

The AS is a small camera mounted on the starshade that determines the alignment of the starshade to JWST and the target star. It must be able to find JWST when the starshade is up to 50km from its commanded position and move the starshade to within 2m of the line-of-sight to the target star. Fig. 11 shows the method of using reflected light from the JWST sunshield as a guiding signal for the AS. Candidate AS instruments are JMAPS and HRI (Table 2), both of

Table 1: Nominal NWP TAC Operations Events

Event	Timescale	Sensor	Position Precision		Details
			Dist.	Angle	
Starshade Retarget	5-30 days	Ground or AS	50km	3'	Slew to new target using NEXT thrusters Get alignment data once/day from ground or AS
Acquire JWST	2-12 hrs	AS	±4m	15mas	If the sunshield is not visible: wait until next JWST pointing maneuver (or ground can insert JWST roll maneuver to illuminate sunshield) Starshade maneuvers to final position Time depends on accuracy of previous step
Alignment Acq. & Calibration	1-2 hrs	AS & Ground	±2m	8mas	Start of JWST cooperative mode JWST maneuvers to ensure sunshield is visible Starshade AS + JWST WSC Mode calibrate alignment JWST acquires target star
Science Observation	1-5 days	AS (+ Ground)	±2m	8mas	JWST performs science observation Starshade maintains alignment using AS or JWST WSC Mode

which have high heritage from previous missions.

A 50 km position error corresponds to 3.4′ at 50,000 km, so the FOV is more than adequate to find the signal from JWST at the hand-off point. On average, 12 stars brighter than 15th magnitude will appear in the astrometric sensor's FOV which serve as references for relative motions, or, with astrometric calibration, for absolute bearing measurements.

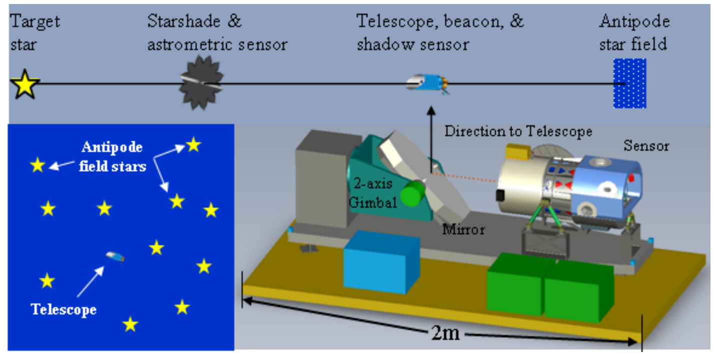


Figure 11: The astrometric sensor on the starshade observes an optical beacon on the telescope to find the telescope's location against antipodal stars for medium alignment.

The strongest visual signal from JWST is reflected sunlight off the sunshield; this reflection is ~90% specular and 10% diffuse. By estimating the diffuse component only, we estimate that there is an average signal of ~12th magnitude from the sunshield over the angular range of interest for NWO alignment (Fig. 12). The specular component will give us a much larger signal for certain angles. Using longer integration times on the astrometric camera, we can also tolerate a weaker signal: down to 15th magnitude is feasible for JMAPS, and potentially even fainter for HRI. In addition, the solar arrays and the bus on JWST will receive significant illumination, large enough to be detectible, but is not included in this calculation. These signals are further enhanced by light reflected off the sunshield and onto the spacecraft. The sunny side of the sunshield is canted back from the line of sight, so in science observation mode, the starshade will be looking at the dark spaces between the layers of the sunshield. During science observation, only a portion of the spacecraft bus will be visible over the edge of the sunshield. JWST can be commanded to periodically perform a small roll maneuver so NWP can see the bright part of the sunshield. If feasible, a white panel could be added near the bus to ensure that JWST is bright enough. A full analysis of the JWST integrated reflected light is the immediate next task of the NWP project.

Table 2: HRI and JMAPS

Capability	HRI	JMAPS
Vis magnitude limit	15	12
Field of View	7′	1.2°
Integration time	3.3 sec	10 sec
Positional uncertainty	4.4 mas	5 mas
Heritage	TRL 9 –Deep Impact	scheduled 2012 launch

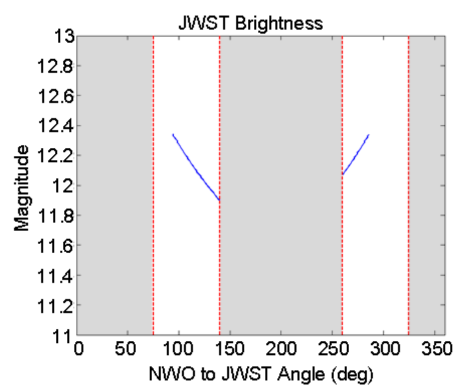


Figure 12: A conservative estimate of JWST brightness, showing that it is brighter than 12th mag. over the angles of interest for NWO. The white regions indicate allowed relative angles between JWST and the starshade during alignment acquisition.

IV. TECHNOLOGY DRIVERS

Technology development for NWP is very similar to that needed for the NWO project (Fig. 13). We refer the reader to the Starshade Technology Development white paper for further information about the technology, or the NWO ASMCS final report (see References section) for more details. There are three tall poles for NWP: 1) Starshade Optical Performance, which involves the need to validate the optical performance of the starshade via simulations and testbeds; 2) Starshade Precision Deployment and Shape Maintenance, were the technology needed for deployment and on-orbit shape maintenance of the starshade needs to be integrated; and 3) Trajectory and Alignment Control, where the technology for alignment with JWST needs to be developed. The first two are the same as for the NWO flagship mission, so they are not discussed here. Technology impacts to JWST can also be thought of as a tall pole, as any impacts to JWST carries significant risks.

The NWP can be implemented with zero impact to JWST as it is planned now. However, minor changes can be implemented at near zero cost in the very near future and make significant improvement in the scientific return should the starshade be flown.

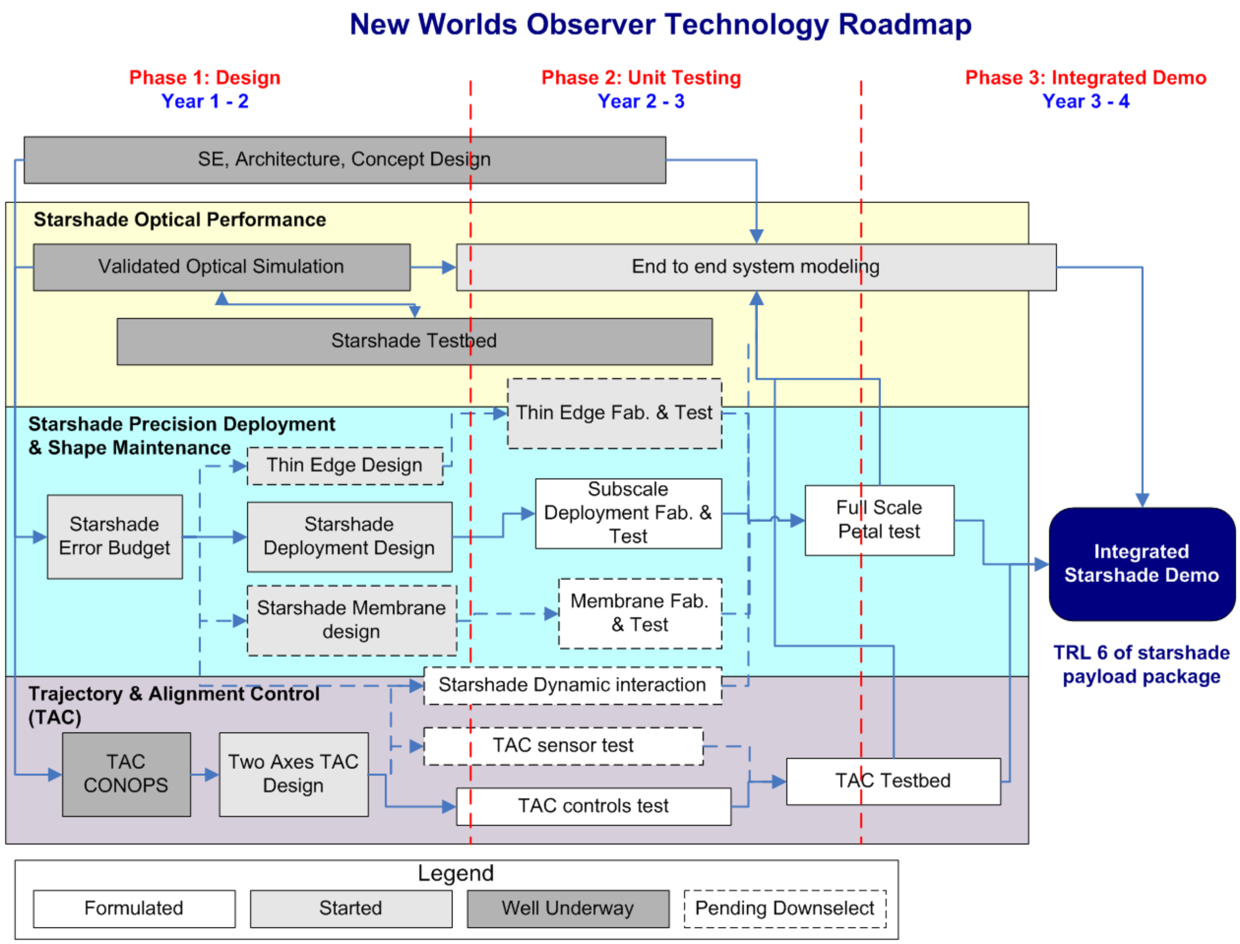


Figure 13: Using existing and heritage components, NWP can be developed quickly. The Starshade can reach TRL 6 in ~30 months.

Alternative Trajectory and Alignment Control Operations Scenario

To further increase the accuracy of the AS, a calibration maneuver is included in the checkout portion of the mission shortly after the starshade arrives at L2. Using no more than 50 hours of JWST time, NWP performs a correlation of the AS output with data from JWST's NIRCam data. The JWST Wavefront Sensing and Control mode in NIRCam includes a pupil-imaging lens (PiL), which can be used to map the pupil plane of JWST. With the starshade in place, NIRCam will measure the profile of the starshade's shadow at the pupil. Having this data and the corresponding AS data during the same epoch will allow calibration of the AS accuracy and precision. Each NIRCam pixel is sensitive to 10.4 nJy in a 10,000 sec integration. Fig. 14 shows the expected starshade shadow profile in the NIRCam F200W band. The average suppression in this band of 10^{-5} applied to a typical m=5 star results in a 0.35 mJy signal, orders of magnitude above the sensitivity threshold of NIRCam.

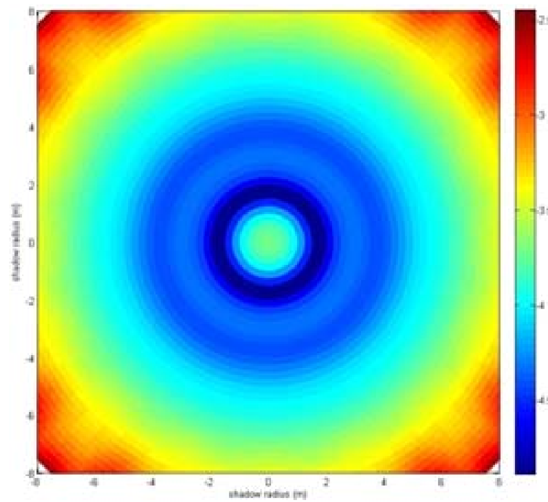


Figure 14: The starshade shadow in the JWST pupil plane. The shadow has an intensity variation of more than 2 orders of magnitude over the JWST aperture in the NIRCam F200W filter.

During the Science Observation mode, the AS may not have adequate signal from the JWST sunshield and this same method may be required to perform alignment. In this case, the alignment loop would have to be closed via the ground. The frequency of such ground contact depends on the location of the spacecraft during the observation. In the worst case scenario, the starshade drifts ~1 m every 17 min. Ground contact will be required in this case once every 60 min, in order to ensure the starshade never drifts out of the ±2 m alignment box. The median, or expected, contact rate is 160 min, and the optimal case is once every 392 min. *We plan to optimize target selection with this criterion to minimize the contact frequency*.

The DSN contact requirement and cadence is determined by the starshade during the Alignment Acquisition & Calibration mode. The starshade determines if there is enough flux from JWST for alignment and, if not, sends the necessary telemetry so that the ground can calculate the required cadence by correlating JWST NIRCam output with starshade telemetry and astrometric data. NIRSpec may still be used in parallel during this operation, but NIRCam observations will be impacted. It is expected that this mode will occupy a total of ~20 min per contact (every 60 to 392 minutes). In the worst case scenario, the total telescope time required to do a NIRCam observation will increase by ~30%.

The DSN cost for 168 hours of continuous contact is ~$304K. For the optimal case, it is approximately $216K. For 30 targets, this is an additional $9M in DSN station costs ONLY (no ground-support personnel costs).

We have assumed no changes to JWST. The next technology development page outlines several minor changes to JWST in order to make alignment much simpler and improve the science return of the mission. We want to stress that NWP is feasible with ZERO modifications to JWST; the list are simply suggestions should NASA see fit to implement them.

Technology Development Mitigated by Minor JWST Upgrades

With very minor upgrades to JWST, we can obtain much more useful science data and lower the risk levels for some of the technical issues. We list below the hardware (Table 3) and operations (Table 4) modifications that will assist the NWP project. These are not necessary changes to JWST, as NWP is feasible with no JWST modifications.

Table 3: Possible JWST Hardware Modifications

Upgrade	Benefit
Different filters on NIRSpec	Reduce red leak to short wavelength and reduce Exoplanet spectrum data acquisition time
Reduce width of small part of a NIRSpec slit	Reduce background light to improve exoplanet spectra S/N
Different filters on NIRCam	Reduce red leak to short wavelength and reduce Exoplanet spectrum data acquisition time
Add passive reflective element on JWST bus	Enhances reflected light signal from JWST to allow AS acquisition

Table 4: Possible JWST Operations Modifications

Upgrade	Benefit	Impact
Allow JWST backup omni to send partial telemetry data from NIRCam to starshade	Bypass Ground for alignment calibration, provide a backup method in case of AS JWST acquisition failure	Additional NIRCam processing software required, minor impact for

A top-level schedule and cost for this development is shown in Table 5. Most of the individual technology elements needed for NWP exist, but they have never been used together. For example, the three major pieces of the starshade deployment system: telescoping tubes, thin edge, and membrane are of high heritage, but have never been combined in this way. Our main task is to integrate the design and test the pieces together as a unit. We believe we have a cost-effective technology development program that can be immediately implemented and bring the system to TRL=6 within 30 months.

Table 5: NWO Technology Development Current TRL level, budget and top level schedule in $M

	TRL	**2011**	**2012**	**2013**	**Total**
1. Starshade Optical Performance	4	2	3		**5**
2. Starshade Deployment & Shape Maintenance	4	3	10	14	**27**
3. Trajectory and Alignment Control	5	1	4	5	**10**
Total		**$5M**	**$17M**	**$19M**	**$42M**

V. ACTIVITY ORGANIZATION, PARTNERSHIP, AND CURRENT STATUS

The New Worlds Probe team will implement a management plan fully compliant with NPR 7120.5D. NWP is intended for a Probe-class Exoplanet mission, and therefore will comply with all organization structure mandated by the AO. We assume an NWP Principal Investigator (PI), is directly responsible to the appropriate NASA agency, such as the ExoPlanet Program Office, for all aspects of the mission.

The organization of the activity as it moves forward is still being determined. PI-level leadership has been provided by Webster Cash at the University of Colorado through the New Worlds Observer Study (supported by GSFC and Northrop Grumman Corporation) and by David Spergel at Princeton University through the THEIA study (supported by JPL and Lockheed Martin Corporation). Given the similarity of the outcomes of those two studies, Cash and Spergel have agreed to remerge their teams. Both NWO and THEIA studied mission architectures that assumed a 4 m UVOIR telescope dedicated and designed to work with the starshade. The Space Telescope Science Institute has joined the NWP consortium and will provide the needed expertise in the operation and use of JWST. John Mather, JWST Project Scientist will act as liaison between the NWP and JWST projects. Thus we believe our team covers well all the needed bases both technically and scientifically.

The NWP team will continue to work on refining the mission concept, understanding mission impacts on JWST, developing technology and the verification & validation plan, and conducting research in our testbeds. Particular attention will be given to addressing schedule critical and JWST related risks. The team continues to work on partnerships with industry and international entities, and growing the science community support for NWP. We are also investigating international participation by agencies such as ESA and JAXA where contributions could reduce the total NASA cost.

VI. ACTIVITY SCHEDULE

The planned operational lifetime of the NWP mission is 2 years with a goal for an extended mission of an additional 1 year. The NWP project schedule is shown in Fig. 15. The schedule assumes a project start date of 2011, but we have given the project in terms of Year 1, Year 2, etc., since the date of the Exoplanet Probe AO is uncertain. Phase A duration is 12 months, leveraging the learning from the NWO and THEIA projects. Phase B duration is 12 months and development (Phases C and D) is 36 months. System-level integration and testing lasts 9 months. Specialized starshade testing facilities will be built for the starshade development. Launch is scheduled for June, 2016, approximately 3 years after JWST launch. This permits JWST to perform its key science and NWP the flexibility to design to changes in JWST performance. NWP will then have a planned operational lifetime of 24 months with JWST.

Reviews will be conducted according to the NASA Procedural Requirements (NPR) document 7120.5D. The Goddard Integrated Independent Review (IIR) process fulfills the NASA imposed requirement within NPR 7120.5D for both Independent Reviews and Critical Milestone Reviews of projects. The IIRs are used to evaluate the status of a flight project at the mission system level and at the major system element level (i.e., spacecraft, instrument(s), and ground system). IIRs are supported by project-conducted Engineering Peer Reviews (EPRs) which assess the status of subsystem or lower assembly levels. The results of the EPRs constitute a key input to the IIRs. The project-level reviews are shown on the mission schedule in Fig. 15.

The critical path lies along the Trajectory and Alignment Control system in the schedule. This represents the (non-mechanical) interface to JWST, and is a critical part to the mission success. In particular, impacts to JWST must be studied and carefully controlled. The design, development, and manufacture of this system is given 36 months to reflect the complexity. The systems integration to the spacecraft is relatively straightforward and can be accomplished within the system I&T schedule.

The NWP schedule includes a total of 12 months of reserve for the starshade and 4 months of reserve for the TAC system, a total staggered reserve of 16 months. Mission schedule reserve is held at 4 months. The NWP budget includes funding for this schedule reserve and is $64.3M.

The starshade/payloads/spacecraft may be developed by a separate vendor from the TAC system to facilitate parallel development in order to accelerate the schedule. The starshade payload development and I&T is 17 months. Starshade spacecraft development and testing is 21 months. Starshade spacecraft launch/early orbit checkout is 21 days and the cruise to L2 orbit and checkout is launch date dependent, with a nominal of ~100 days. Transition to normal operations is ~4 months after launch with the mission operating 2 years.

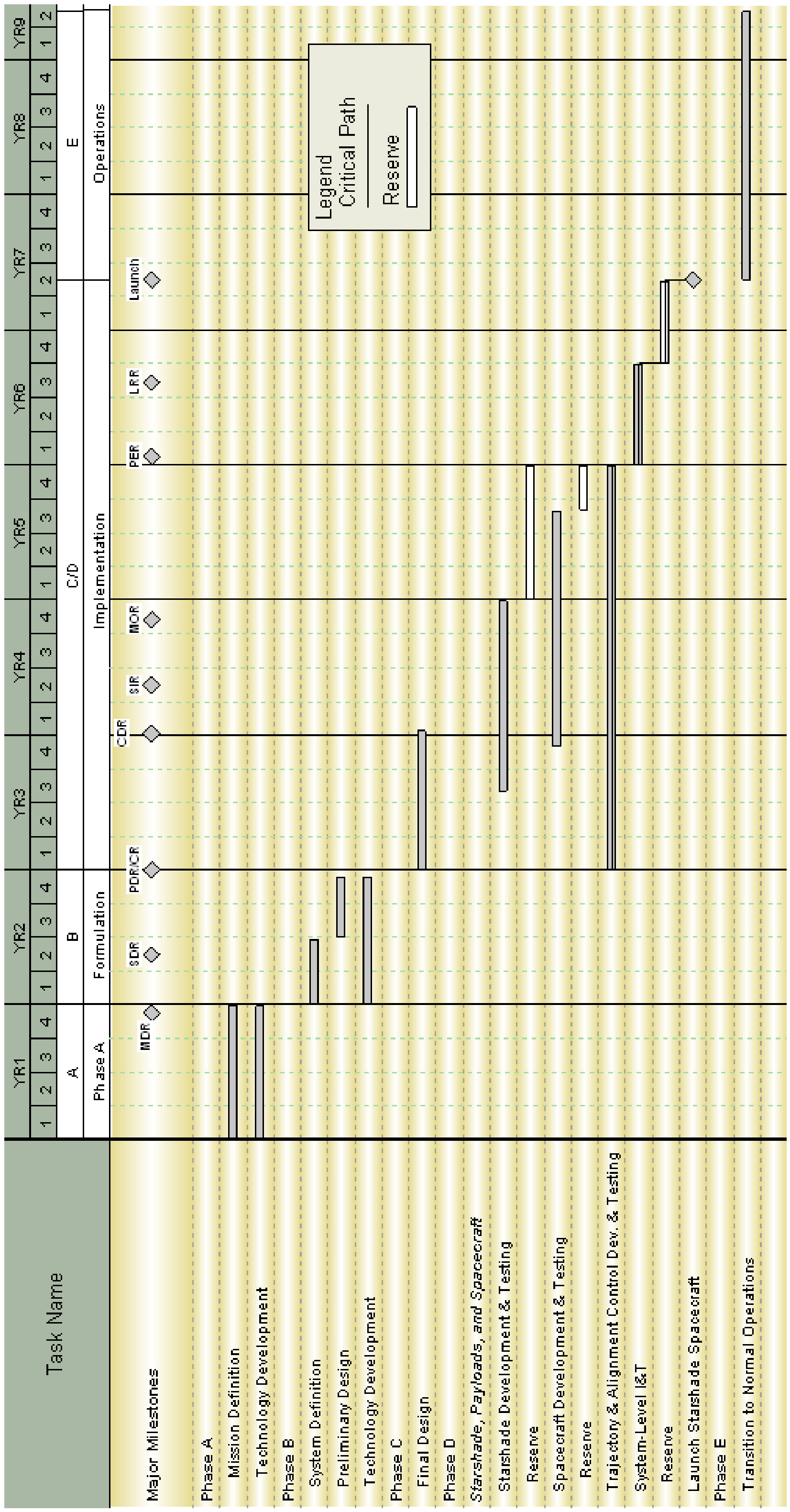


Figure 15: NWP Proposed Project Schedule

VII. COST ESTIMATE

Costing Assumptions and Details

The following assumptions were made in developing the baseline mission cost. The Project start is in fiscal year 2011, with a Phase A duration of 1 year, Phase B duration of 1 year, Phase C/D duration of 3 years, and a Phase E duration of 2 years of cooperative operation with JWST. The starshade payload and spacecraft will be built in parallel with the Trajectory and Alignment Control system. Specialized test facilities at NGC are required for the starshade. One EELV is needed with to launch the starshade in June 2016. Funded schedule reserve is included in the budget at $64.7M. Thirty percent costing reserves were applied to all cost elements except EPO and launch vehicle.

Table 6: Cost Estimating Methods by Work Breakdown Structure Element

WBS Element	Method
1.0 Project Management	Grassroots by GSFC New Business Office, from 2006
2.0 System Engineering	Grassroots by GSFC New Business Office, from 2006
3.0 Safety & Mission Assurance	Grassroots by GSFC New Business Office, from 2006
4.0 Science & Technology	Grassroots estimate from GSFC science directorate, grassroots estimate from NGC and Ball Aerospace, 2009
5.0 Starshade	Grassroots estimate from NGC, from 2009
6.0 Spacecraft	Grassroots estimate from IDC, from 2009
7.0 Mission Operations	Grassroots estimate from IDC, from 2006
8.0 Launch Vehicle	ROM from IDL, 2009
9.0 Ground Systems Development	Grassroots estimate from IDL, from 2006
10.0 Mission I&T	Grassroots from NGC and Ball Aerospace
11.0 EPO	ROM from IDL

Cost Estimating Methodology

Our costing efforts were centered on achieving realistic estimates for a probe class mission. We have studied the cost in several independent ways: NWO team grassroots (GR), rough order of magnitude estimates (ROM), GSFC Integrated Design Center (IDC) PRICE-H parametric, grassroots, and 70% confidence level estimates. The Spacecraft, Technology Development, and Starshade Payload costs incorporate latest cost analysis and development as of the writing of the document. Cost elements such as Science, Mission Operations, Ground Systems, Project Management, and System Engineering uses escalated costs developed in 2006 for a Discovery proposal. The starshade cost estimate was generated by NGC with grassroots estimates based on parts and drawing counts. Non-recurring engineering (NRE) incorporates design time estimates from the parts and drawing counts. The starshade cost includes one qualified and tested Astro telescoping boom assembly, one four-boom quarter circle qualification model of the starshade assembly, one 16-boom flight unit, and facilities costs. Costs for Project Management (PM), Mission Systems Engineering (MSE), and Safety and Mission Assurance (SMA) are validated by IDC grassroots calculations. Education and Public Outreach cost is a ROM estimate at 0.5 percent of the total mission cost without the launch vehicle and before reserves and contingency are applied. Table 6 summarizes the cost methods by Work Breakdown Structure (WBS) cost element.

Table 7: NWP Project Element Estimate in 2009 Fix Year Dollars

	Base	W/Contingency
Starshade	**427.4**	**555.7**
Starshade Payload	129.6	168.5
Spacecraft	217.0	282.1
Astrometric Sensor	60.8	79.0
Astrometric System	20.1	26.1
Science and Technology	**65.4**	**85.0**
Science	21.4	27.8
Technology Development	44.0	57.2
Mission Ops, Ground, System I&T	**20.6**	**26.8**
mission operations	10.8	14.0
ground systems	3.5	4.6
Mission I&T	6.3	8.2
Mission subtotal	513.4	752.5
Mission wrappers	**48.8**	**127.4**
PM, SE, SMA	46.2	60.1
Funded Schedule Slack	0.0	64.7
EPO	2.6	2.6
Launch Vehicle	**180.0**	**180.0**
MISSION TOTAL	**742.2**	**1059.9**

Cost Results

In order to provide an easy way to see the cost breakout of specific flight/ground components, we present Table 7. We have broken out separate costs for the telescope and starshade, science/technology, total mission operations/ground development and systems I&T, and mission wrappers. The total starshade system with spacecraft cost is $427M; total science and technology is $65.4M; the total mission operations/ground system development and I&T costs are $20.6M, PM/MSE/SMA costs are $46.2M, and EPO at $2.6M. The cost for one EELV (specifically, one Atlas 541) launch vehicles is $180M. One can see that the total lifetime cost including technology development for NWP is $742 Million dollars, and $1060 million with 30% contingency applied on everything except launch vehicle, and including a $64.7 million dollar funded schedule slack.

We have attempted to use the most conservative path when in doubt, and the relatively advanced state of the key technologies gives NWP lower cost risk than is often encountered. Further into the development of NWP we would expect to invite international participants, most likely ESA and JAXA. Their contributions would reduce the total cost to NASA. A detailed cost assessment of the NWP project is underway.

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